# WEIGHING AT SEA WITH A GIMBAL PLATFORM

by

Charles Manfred St. Laurent

United States
Naval Postgraduate School

# THESIS

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Charles Manfred St. Laurent
Lieutenant Commander, United States Navy
B.S., United States Naval Academy, 1961

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ABSTRACT

The use of a gimbal platform with two degrees of freedom under dampened pendulum motion allows a standard laboratory balance to be used to weigh scientific samples at sea. The maximum sample weight tested was approximately 120 grams, while the average accuracy obtained in samples ranging from 1 to 120 grams was 0.10% (± .05%). The sea conditions under which at sea weighings can be conducted vary with the size of the research vessel. The gimbal platform does not provide the stabilization necessary under adverse sea conditions.

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# I. INTRODUCTION

With the advent of an increased interest in the OCEANS, by both civilian and government agencies, there has been a paralleling advance in the development of new and varied instruments to be used for gathering and analyzing data.

An instrument that has been developed for many years but has not been able to provide accurate results on a rolling and pitching vessel is the standard laboratory balance. If this instrument could be used on a vessel, such that the weighing results were completely or even partially independent of the vessel motion, then in many instances analysis of oceanographic data could begin the minute samples were received, rather than having to wait until an inport period. Reduction of somewhat unproductive at sea periods, where oceanographic samples are available, but not processable, can be achieved through the use of a simple gimbal platform which allows the oceanographer to use a laboratory balance at sea under certain sea conditions.

There are three specific instances where the satisfactory use of a balance would give the "scientist at sea" a quicker analysis of his data and make it more reliable. The first is in the taking of ocean bottom samples by means of a coring device. Approximately seven out of the thirteen major engineering parameters used to describe the ocean bottom are directly or indirectly dependent upon soil sample weighing. At present the cores are taken from the ocean bottom, sealed at the ends and immersed in salt water to prevent desiccation. The cores are then analyzed at the shore laboratory at a later date. The advantage of knowing what the bottom conditions are while on station, rather than weeks or months later backe in the laboratory, are apparent.

A second specific example is in the field of biological oceanography. During a six month euphasid gathering expedition in the North Atlantic, freezing of the specimens to permit analysis upon completion of the cruise resulted in unreliable dry weights because the specimens tended to dry even in the deep freeze. [Raymont, et al. 1969].

The third example is not related to oceanography, but concerns the determination of the presence of contaminants in military aviation fuel aboard naval aircraft carriers. The method used at present is a spectrophotometric analysis technique that occasionally gives erroneous results due to the abnormal light reflection characteristics of certain contaminant particles [Mr. B. Faulhaber, Personal Communication]. This results in fuel being considered satisfactory or contaminated when it may be just the opposite. A direct weighing of the filters would eliminate this possible error.

Thus, if the laboratory balance can be made to satisfactorily perform at sea, the oceanographer will be able to enhance the gathering of data by providing a means to quickly and accurately analyze the data "now, not later".

## II. BACKGROUND

During the summer of 1966, the U. S. Bureau of Mines Branch in Tiburon, California invited various balance manufacturers to demonstrate the capabilities of their respective balances during an at sea evaluation aboard a small vessel. The results were unsatisfactory [Higinbotham, Personal Communication]. It was decided to explore the possibility of using a gimbal platform to place the balances on while conducting the at sea weighings.

A surplus Navy MARK XIV MOD 1 Sperry Gyroscope was obtained and modified to provide two degrees of freedom. By employing a pendulus motion system to keep the balance platform horizontal and to make the laboratory balance independent of ship motion, it was believed that satisfactory weighing at sea could be accomplished.

This apparatus was placed aboard the research vessel Virginia City and used to weigh ocean bottom samples during an offshore drilling expedition covering the months of July-August 1967. The results obtained were within the Bureau of Mines accepted accuracy [Higinbotham, et al., 1969], however, the weighings obtained were not correlated to the existing sea conditions and corresponding ship response for an empirical evaluation of the gimbal. Also, there was a lack of data regarding the pendulum motion.

Subsequently, the gimbal platform was made available to the Naval Postgraduate School's Department of Oceanography for further analysis and evaluation aboard various research vessels.

The principal of a gimbal supported arrangement to assist in instrument measurements at sea was first used in conjunction with gravity measurements [Dehlinger, 1964]. The at sea gravity measurement results

obtained with a La Coste and Romberg gimbal supported gravity meter show a high degree of accuracy when the horizontal and vertical motions of the vessel are nearly uniform and approximately sinusoidal. Also, the best measurements were obtained when the sea was parallel to the ship's motion [Dehlinger, 1964].

An improvement to the gimbal supported gravity meter was made by redesigning it operation for use on a stabilized platform which more nearly restricted the instrument motion to a single degree of freedom [La Coste, et al., 1967]. Evaluation of this new system has shown that the gravity measurements have been as accurate as before, even under adverse sea conditions. Only under particularly adverse sea conditions, when the cross-coupling effects of the horizontal and vertical accelerations were excessive, did the gravity meter not perform well [Lafehr, et al., 1967].

Thus it appears that the use of a free gimbal platform is the first step in the development of a stabilized platform for satisfactory at sea weighings.

## III. GIMBAL PLATFORM DESCRIPTION

The gimbal platform used for conducting the at-sea weighings was a modified surplus Navy gyroscope, MARK XIV Mod I that was manufactured by the DODGE DIVISION of Chrysler Corporation, Detroit, Michigan, under license from Sperry Gyroscope Company, Inc. (now called Sperry Rand Corporation) in 1942 [SPERRY INSTRUCTION BOOK 17-1400CC, 1942]. The general characteristics are given in Table I. The internal assemblies of the unit were removed, while the inner and outer gimbals, spider element, outer gimbal supporting springs and dash pot assembly were retained in place as illustrated in Figure 1.

TABLE I

GIMBAL PLATFORM CHARACTERISTICS

| | |
|---|---|
| Height | 35 inches |
| Maximum Width | 30 inches |
| Total Weight[1] | 285 pounds |
| Pendulum Weight | 64 pounds (maximum) |
| Pendulum Length | 25 inches |
| Table Top | 20 by 21 inches |
| Maximum Roll | 15 degrees |

Note: [1]Assembly can be separated into two units for mobility.

A 20 inch by 21 inch balance platform was constructed out of fiber board and attached to the spider element. To provide for proper positioning of the balance, a grid pattern of two inch squares was drawn on

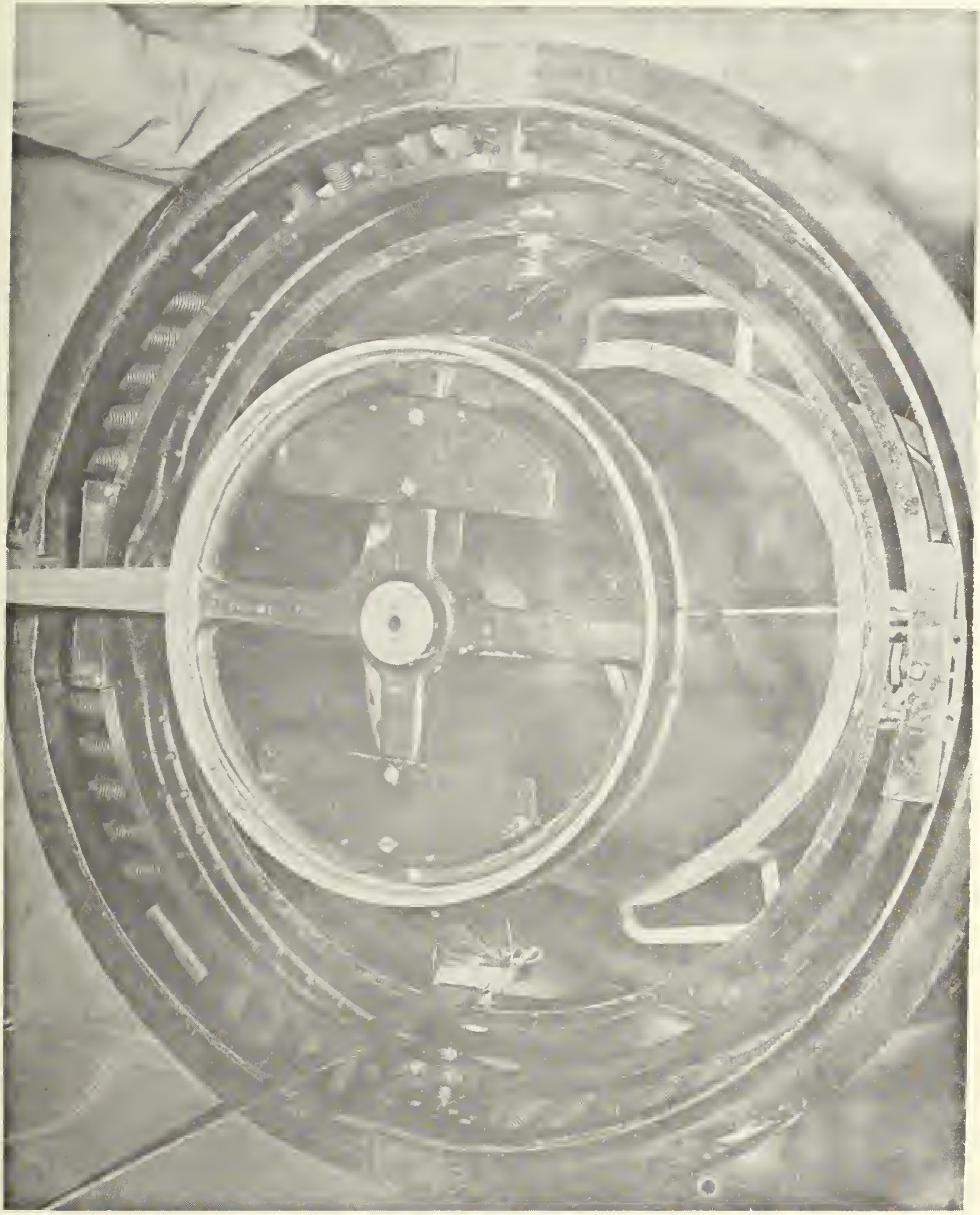

Figure 1. Gimbal Assembly Showing Inner and Outer Gimbals, Pendulum, Dampening Oil and Tank

the platform. This allowed the balance position to be determined in the laboratory and be permanently marked for use at sea.

Attached to the spider element and extending 26 inches below the center of the platform was a 1.26 inch diameter steel rod with a bottom retaining piece. The retaining piece was used to support the removable lead weights at the end of the pendulum. A total of seven lead weights were used, six of which weighed nine pounds and the seventh ten pounds. In order to assure that the pendulum weight was evenly distributed about the rod, the weights were usually added in pairs so that the slots, as shown in Figure 2, were 180 degrees apart on adjacent weights. With all seven weights used the height of the cylindrical shape of weights is seven and one-quarter inches.

The gimbal apparatus consists of three major components:

| COMPONENT | WEIGHT (lbs) |
|---|---|
| Top Half | 160 |
| Bottom Half | 110 |
| Oil Tank | 15 , |

which makes the assembly portable and allows it to fit through a standard shipboard hatch.

The outer gimbal was supported in the assembly by 47-3/4 inch long springs. This arrangement prevented the gimbal assembly from absorbing any sudden impacts of shock as a result of ship motion. The normal orientation of the unit was with the inner gimbal trunions placed athwart-ships, thereby putting the outer gimbal bearings fore and aft, thus allowing the outer gimbal, which had two dash pot dampeners located 90 degrees from its bearings, to compensate for any violent rolling the ship might encounter. Figure 3 shows the dash pots.

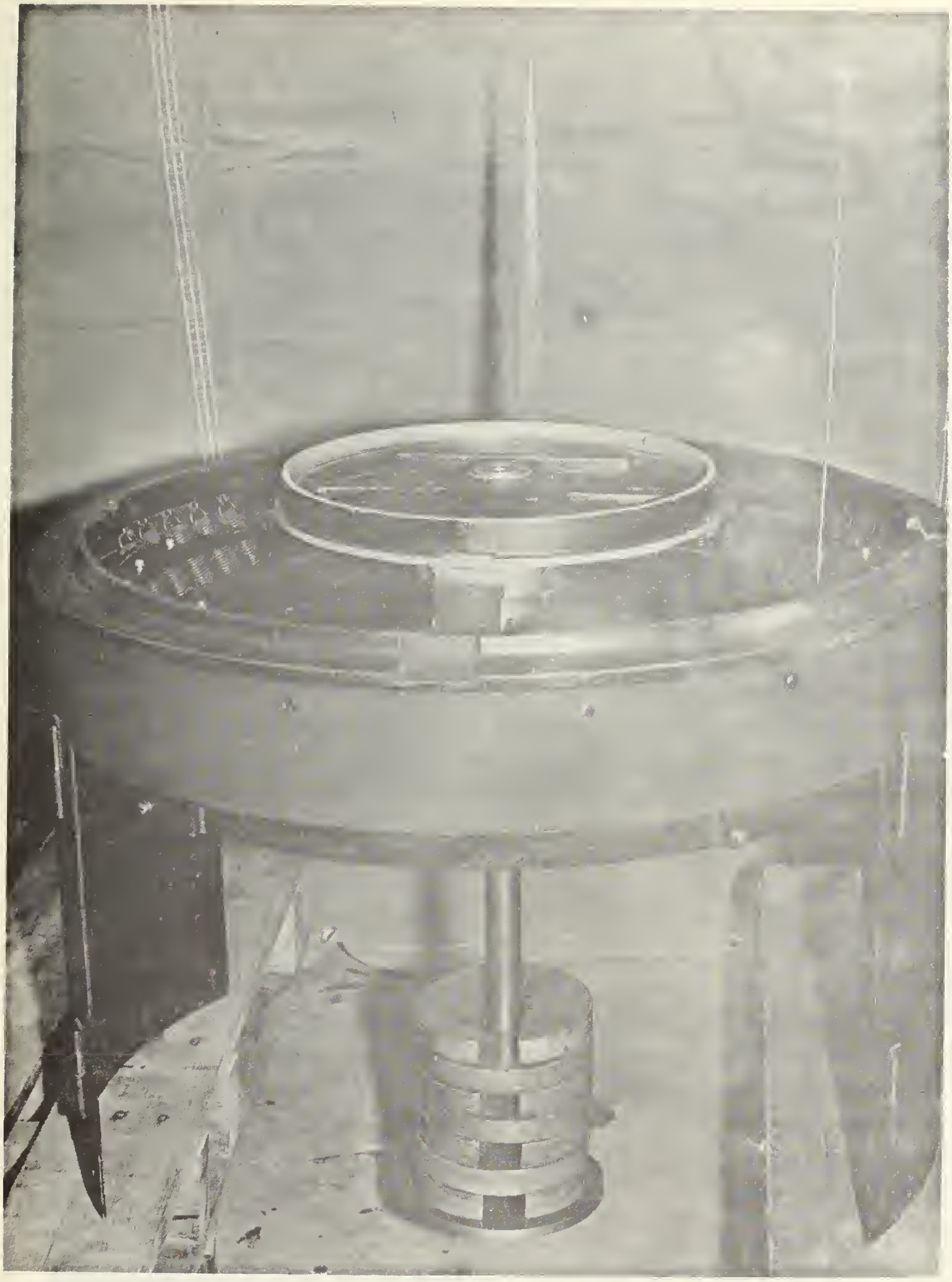

Figure 2. Upper Assembly Component With Inner Gimbal, Pendulum, and Pendulum Weights

Figure 3. Upper Assembly Component With Outer Gimbal and Supporting Springs, and Outer Gimbal dash pots

TABLE II

DAMPENING FLUID SPECIFICATION

| FLUID | TEMP (°F) | SSU [1] (sec) | API Number | Specific Gravity | DENSITY [2] (lb/gal) | DENSITY [2] ($gm/cm^3$) | VISCOSITY (cs) [3] | VISCOSITY (cp) [4] |
|---|---|---|---|---|---|---|---|---|
| SAE 10W | 60° | 233 [5] | 29.1 | 0.8816 | 7.341 | 0.7329 | 49.62 | 36.37 |
| | 70° | 220 [5] | | 0.880 [3] | 7.249 | 0.7237 | 46.80 | 33.87 |
| | 100° | 182 [6] | | 0.870 [3] | 7.245 [6] | 0.7233 | 39.02 | 28.22 |
| | 210° | 45.7 [6] | | 0.825 [3] | 6.800 | 0.6788 | 5.94 | 4.03 |
| SAE 50W | 60° | 1665 [5] | 25.6 | 0.8984 | 7.482 | 0.7469 | 359.54 | 268.54 |
| | 70° | 1560 [5] | | 0.890 [3] | 7.411 | 0.7398 | 336.90 | 249.24 |
| | 100° | 1250 [6] | | 0.875 [3] | 7.287 [6] | 0.7275 | 269.70 | 196.21 |
| | 210° | 96.6 [6] | | 0.850 [3] | 7.002 | 0.6990 | 19.57 | 13.68 |
| SAE 90W | 60° | 1205 [5] | 24.4 | 0.9100 | 7.578 | 0.7565 | 260.14 | 196.80 |
| | 70° | 1125 [5] | | 0.905 [3] | 7.455 | 0.7442 | 242.90 | 180.77 |
| | 100° | 905 [6] | | 0.900 [3] | 7.414 [6] | 0.7401 | 195.30 | 144.54 |
| | 210° | 83.2 [6] | | 0.860 [3] | 7.085 | 0.7073 | 16.33 | 11.55 |

[1] Saybolt universal viscosity

[2] From Nelson (1958)

[3] Kinematic viscosity in centistokes

[4] Specific viscosity in centipoise

[5] Linear interpolation

[6] From manufacturer's specifications

The maximum table roll that could be sustained by the apparatus was 15 degrees in both directions. This was a physical limitation in that beyond this angle the pendulum bob came in contact with the sides of the oil tank. Figure 4 shows the platform approaching its roll limit during a sea trial.

Table II lists the dampening fluid characteristics of the three different oils that were used to achieve viscous damping of the pendulum motion. The fluids were purchased from a local distributor and are standard automobile lubricants. The 10W and 50W oils are automobile engine lubricants while the 90W oil is a transmission gear lubricant. The temperature of the oils during the at sea weighings ranged from 62°F to 74°F. However, during each individual sea trial the temperature varied from one to two degrees.

Approximately eleven gallons of fluid were required to keep the pendulum weights continually submerged. The relative magnitudes of the absolute viscosity is shown in Table III.

TABLE III

RELATIVE VISCOSITY OF DAMPENING FLUIDS

| | TEMPERATURE | | | |
|---|---|---|---|---|
| FLUID | 60°F | 70°F | 100°F | 210°F |
| 10W | 1.0 | 1.0 | 1.0 | 1.0 |
| 50W | 7.4 | 7.4 | 7.0 | 3.4 |
| 90W | 5.4 | 5.3 | 5.1 | 2.9 |

The gyro assembly had a base plate that had four three-quarter inch by three inch slots for mounting the unit to the deck of a ship. However, when the sea trials were conducted, it was found that the unit could

Figure 4.  Gimbal Platform Operating at Sea

easily become immobilized by the placement of sandbags around the base plate and by use of two inch by six inch planks properly positioned as retainers. Only in rough seas did the gimbal platform tend to move when not secured. Figure 5 shows the two pointers and the two plexiglass plates used to record the movement of the table in the two degrees of freedom. Also, Figure 5 illustrates one method of holding the platform secure by means of sandbags and planks.

Figure 5. Gimbal Assembly Secured by Sand Bags and Planks Showing The Two Visual Angle Indicators for each Axis Rotation

## IV. BALANCES EVALUATED

Initially six of the seven balances listed in Table IV were taken to sea to obtain a preliminary evaluation for guidance in scheduling further sea trials. Of the six, only balances A and B were judged to warrant further considerations. The other four balances D, E, F, G, were eliminated because of one or more of the following reasons: (a) the accuracy achieved was less than the acceptable limits, (b) there was insufficient internal balance dampening to eliminate excessive moment in the balance read out, and/or (c) the net weight of the balance was excessive and impaired the effective operation of the pendulum. This last effect is discussed in Section VII and can be assumed to be partly responsible for the rejection of balances due to (a) and (b) above.

The particular balances were selected because they represented the balances of three major manufacturers that had operating features which were considered desirable for at sea weighings on a gimbal platform. Also, they were readily available for the duration of the research.

When considering the use of a balance in a laboratory, due care must be given to whether the balance can provide the desired accuracy as well as to its ability to satisfactorily perform under specified environmental conditions. This is true for both shore laboratories and sea going laboratories. However, operation of a balance at sea presents a few additional problems that are not found ashore. The most critical one is the effect that a rolling and pitching vessel has on the balance mechanism through the resulting accelerations and forces in six degrees of freedom. These freedoms are classified as rotational (pitch, roll, yawl), and translational (heave, surge, sway) motions.

TABLE IV

BALANCE DATA

| | BALANCE A | BALANCE B | BALANCE C | BALANCE D | BALANCE E | BALANCE F | BALANCE G |
|---|---|---|---|---|---|---|---|
| CAPACITY (grams) WEIGHING RANGE | 0-1 | 0-10 | 0-160 | 0-200 | 0-1200 | 0-2000 | 0-4500 |
| TARE | .5 | 110 | 48 | 50 | 100 | 325 | 500 |
| TOTAL | 1.5 | 120 | 208 | 250 | 1300 | 2325 | 5000 |
| ACCURACY | $.1 \times 10^{-6}$ | 0.005 | 0.0005 | 0.015 | 0.005 | 0.1 | 0.2 |
| DAMPING | Magnetic | Silicone Fluid | Silicone Fluid | Air | Magnetic | Silicone Fluid | Silicone Fluid |
| NET WEIGHT (lbs) | 11.5 | 11 | 25 | 12 | 25 | 35 | 30 |

Particular balance characteristics which are of importance to individual balance performance are:

a. Sensitivity to temperature changes.
b. The corrosion resistant property of the balance.
c. Influence of air currents on the balance.
d. Principle of weight determination.
e. Level dependence requirement for proper operation.
f. Vibrational influence on the weight readings.
g. Method of weight reading presentation.
h. The net weight of balance.
i. Power requirement of balance.
j. Maintenance requirement of balance.

The first three characteristics are not considered to be critical to the use of a balance on a ship because the temperature of a location can be readily controlled and stray air currents can easily be eliminated. Additionally, even though the balance used on a vessel would be exposed to a corrosive salt environment, balance manufacturers presently utilized corrosive resistant materials in their construction because of the many different environments in which instruments are used and because of the corrosive properties of many materials requiring weighing.

The remaining seven general balance characteristics are important when considering a unit for use at sea and are discussed below without making reference to specific instruments.

Due to the vessel motion, a balance must operate in such a way that the ship motion will have a minimum effect on the balance motion. An apparent and basic illustration of a detrimental affect can be seen through the use of a simple spring scale. As a ship rises and falls the object being weighed would tend to increase the spring oscillations because of the accelerations induced on the mass by the ship motion.

Therefore, a shipboard balance should have a minimum number of moving parts and be capable of dampening out unwanted balance motion or at least reducing the motion to a minimum.

The major characteristic of balance operation that imposes a limited shipboard use is that of level dependence. A balance that is extremely sensitive to a condition of absolute levelness can not be considered for use on a ship. The instrument must be able to tolerate slight deviations from level. However, a balance will not provide the degree of accuracy and reproducible weight determinations required if its operation is not level dependent to some degree.

Vibration can be effectively controlled on board a ship by the proper choice of the balance location. However, because of the nature of a vessel's irregular motion caused by wind and wave forces, some vibration can be expected and must not adversely affect the balance components. A balance should not become easily mis-aligned due to minor vibrations. Finally, the balance should be located on the vessel centerline and as near to the center of pitch as possible so as to minimize the effect of the vessel motion.

The method for the determination of the equilibrium condition of a balance on a ship is not a well defined procedure. It will vary with the method by which the balance presents the sample weight, the vessel motion, and the experience of the operator. This experience is extremely important and as a sailor learns his ship, so does the operator learn his balance and can thus develop the sixth sense of knowing when it is in equilibrium. If a balance utilizes a magnified optical readout then additional problems may arise. With this type of system it is extremely hard if not impossible to weigh at sea. Any slight vibration causes the

scale numbers to become blurred and unreadable and if the balance principle of operation causes a slight oscillation about the unknown equilibrium position, the visual presentation of numbers oscillating back and forth does not allow the operator to estimate equal swings about a reference number. Consequently, a balance that employs a mechanical readout, i.e., a pointer against a scale of equal divisions without numbers, allows the operator to estimate with very good accuracy the condition of equilibrium.

The net weight of the balance may be of great importance as evidenced from the use of the gimbal platform described in Section III and its corresponding pendulum motion as discussed in Section VII. The weight of the balance should be minimized because even with a motorized stable platform, if the weight is not evenly distributed about the center of rotation, counterbalancing of the balance weight must be accomplished to maximize the stabilized platform performance.

The possible power requirements of a balance requires that the proper voltage and current is maintained for accurate balance operation. This would not normally be a problem on large oceanographic research vessels, but on smaller ships that do not have sophisticated generators and regulators, the power supplied may vary and consequently affect balance operation.

The final characteristic, that of maintenance requirements, could become critical on extensive oceanographic research cruises. A balance that requires frequent adjustments or checks by a factory representative would not be desirable, nor would one whose operation did not permit minor adjustments.

Balance A was a standard mechanical balance using torsion bands and the principle of substitution weighing. With substitution weighing, the comparison between two masses is made on one and the same lever arm. This approach eliminates the error torque. This torque is proportional to the difference in the lengths of the two lever arms as found with a beam and middle fulcrum point arrangement [Biétry, 1958]. The torsion bands eliminate both a knife edge fulcrum and moving parts. Silicone fluid was utilized for rapid dampening.

Balance B was an electro-magnetic balance which operated on the principle of weighing by counterbalancing against a known and calibrated electromagnetic force [Cahn, 1962]. The principle limitation in this case is that of weight range, because with large samples (> 1 gram), higher electromagnetic forces require excessively large torque motors and currents. Figure 6 shows a simplified diagram of a Cahn Electrogram-balance.

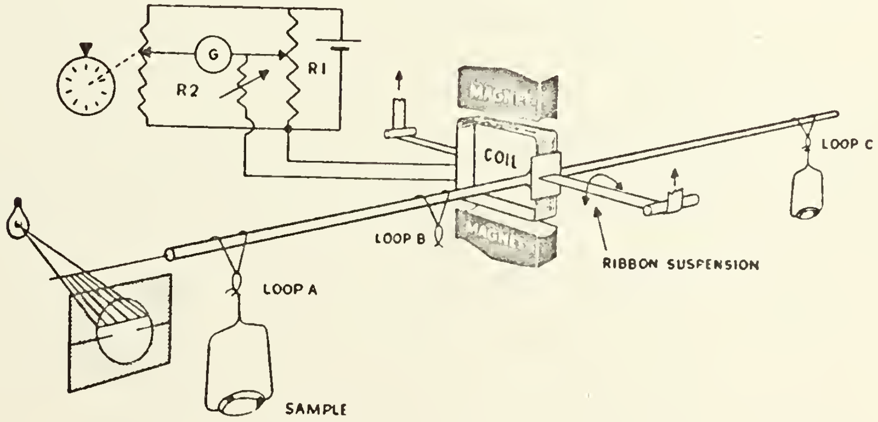


Figure 6. Gram Electrobalance Diagram
[Cahn, 1962]

## V. PROCEDURE

The general procedure in the collection of at sea weighing data was to repeatedly weigh specific samples on one balance at a time while varying the pendulum weights and the viscous dampening medium. For example, a shipboard location was first selected for the gimbal platform. Then the dampening oil was chosen. Next a range of samples was weighed with one specific pendulum weight. The pendulum weight would then be increased and the samples weighed again. When the last pendulum weight was used the dampening oil was changed and the procedure of varying the pendulum weights repeated. The complete operation was repeated with a new balance or at a new shipboard location. Hopefully, during this period, the vessel maintained the same heading in relation to the sea conditions. However, as discussed in Section VI, positive control of the vessel was not always possible due to other requirements.

The majority of samples used were made out of commercial aluminum foil folded to various thicknesses and stored in aluminum tins. The heavy samples were either samll lead weights stored in aluminum tins or plastic snap top vials filled with paper clips.

Prior to the at sea weighings, the samples were weighed in the laboratory on the balances which were to be taken to sea. After the sea trial, the samples were again weighed in the laboratory. This last weighing was primarily a check to detect for possible damage to the balance which might have been incurred during transit or while on board the vessel. In practice all post-sea trial weighings compared exactly with the pre-sea trial weighings. Occasionally a standard class S weight was used at sea. However, because of the whole gram multiple of the

sample, the reading was very often above or below the exact gram weight when estimating the balance equilibrium position. This occurred only when using a balance that required a dial manipulation to load the balance first in steps of even gram values and then in fractions of a gram. The standards that were used as samples are tabulated in Appendix A.

Figure 7 shows the method by which unbiased readings were obtained with Balance A, even after repeated weighings of the same samples. The operator assumed a position such that the readings were obtained by looking directly down at the pointer, while the weight settings on both the coarse and fine dials are hidden from view, but still available for manipulation. The operator looked at the weight dials and read the sample weight only after determining the condition of equilibrium. Naturally, when using a balance with an optical read out, this procedure was not necessary.

In conjunction with the at sea weighings, the environmental conditions were noted at least once an hour or after each individual weighing. The tabulated tables of sea conditions are found in Section VI.

The exact position of each balance was determined in the laboratory such that the pendulum remained as nearly in the vertical as possible. In this way the balance weight was evenly distributed about the center of rotation and did not create adverse moments to influence the pendulum motion. Also, the balance was then in a level condition. These positions were marked on the platform grid lines and then used to place the balance correctly when at sea. The grid lines can be seen in Figure 7.

Figure 7. Weight Determination Procedure

## VI. RESEARCH VESSELS EMPLOYED

Conducting repetitive experiments at sea presents many problems, not the least of which lies in the interpretation of the data. It is apparent that it is impossible to achieve identical "laboratory" conditions under which different tests of the same nature are being conducted. In order to obtain data on at-sea weighings that covered a wide spectrum of conditions, three different oceanographic research vessels were employed. The general vessel characteristics are tabulated in Table V and represent in size the majority of oceanographic vessels that are presently employed by various government agencies, civilian firms, and universities.

TABLE V

GENERAL SHIP INFORMATION

| CHARACTERISTICS | NPS 63 FOOT VESSEL | HOPKINS MARINE STATION VESSEL PROTEUS | USNS OCEANOGRAPHIC VESSEL T-AGOR-14 |
|---|---|---|---|
| BUILT | WW II | 1946 | 1969 |
| CONVERTED | 1963 | 1969 | - |
| LENGTH | 63 ft | 100 ft | 208.3 ft |
| BEAM | 13.75 ft | 24.16 ft | 39.4 ft |
| DRAFT | 3.25 ft | 11.6 ft | 14.25 ft |
| DISPLACEMENT | - | 186 tons | 1339 tons |
| CREW | 4 | 6 | 26 |
| SCIENTIFIC COMPLEMENT | 2 | 9 | 15 |

The Naval Postgraduate School oceanographic research vessel, shown in Figures 8 and 9, is a Naval air-sea rescue boat which was converted


Figure 8. NPS Research Vessel Showing Pilot House and Wet Laboratory Locations


Figure 9. NPS Research Vessel Showing Wet Laboratory Location

for basic oceanographic work in 1963. The boat is mainly used for familiarizing students with oceanographic instruments and for limited research in Monterey Bay.

Figure 8 shows the wet laboratory where the gimbal platform was located. This location places the platform 1.2 feet above the water line, on the vessel center line and 45 feet from the bow. Assuming the center of pitch of the vessel is approximately 60-80 percent of the ship length from the bow [Rakoff, 1962], this places the platform in the most advantageous position for minimizing roll and pitch effects.

On the sea trials of the 15th of May and the 13th of July the vessel was positioned with the bow directed into the swells with its propulsion being used to merely maintain the proper heading. Under these conditions the vessel can be considered to be experiencing motions in the plane of symmetry, i.e., surging, heaving, and pitching [Korvin-Kroukovsky, 1961]. The actual sea conditions under which the weighings were made on the NPS vessel are found in Tables VI and VII.

The research vessel PROTEUS is owned and operated by Hopkins Marine Research Station, a marine biology extension of Stanford University. The vessel is a converted fishing boat and is shown in Figures 10 and 11. The gimbal platform was located in the main laboratory space directly above the shaft, 3 feet below the water line, and 61 feet from the bow. Using the 60-80 percent assumption in locating the center of pitch, the gimbal assembly was again found to be located in a favorable position. The gimbal's position is indicated in Figure 12. Two weighing trials were held while biological trawling was conducted and, as a consequence the ship's relative position with regard to the sea conditions could not be controlled.

TABLE VI

SEA CONDITIONS ON 15 MAY 1970

VESSEL: NPS

| WEIGHING[1] | 27/10 | 45/10 | 64/10 | 27/50 | 45/50 | 64/50 | 27/90 | 45/90 | 64/90 |
|---|---|---|---|---|---|---|---|---|---|
| TIME | 0930 | 1015 | 1050 | 1153 | 1215 | 1240 | 1310 | 1350 | 1410 |
| SWELL DIRECTION (degrees true) | 330 | 330 | 330 | 330 | 320 | 320 | 330 | 330 | 330 |
| SWELL HEIGHT (feet) | 1-2 | 1-2 | 1-2 | 1-2 | 1-2 | 1-2 | 1-2 | 2-3 | 2-3 |
| WIND DIRECTION (degrees true) | 340 | 000 | 355 | 310 | 310 | 330 | 340 | 340 | 340 |
| WIND SPEED (knots) | 3-5 | 3-5 | 3-4 | 1-2 | 1-2 | 0-2 | 0-1 | 1-2 | 1-2 |
| SHIP HEADING (degrees true) | 300 | 325 | 330 | 320 | 310 | 320 | 340 | 340 | 340 |
| SHIP SPEED (knots) | 0 | 0 | 0 | 0 | 0 | .5 | .5 | 0 | 0 |
| WATER DEPTH (feet) | 90 | 95 | 90 | 100 | 90 | 90 | 95 | 90 | 90 |
| MAXIMUM SHIP ROLL (degrees) | 2-3 | 2-3 | 2-3 | 2-3 | 2-3 | 2-3 | 2-3 | 2-3 | 2-3 |
| MAXIMUM SHIP PITCH (degrees) | 1-2 | 1-2 | 1-2 | 1-2 | 2-3 | 2-3 | 1-2 | 1-2 | 1-2 |

[1]Represents pendulum weight (lbs) and S.A.E. oil weight number.

TABLE VII

SEA CONDITIONS ON 13 JULY 1970

VESSEL: NPS

| WEIGHING | CASE A AND 18/50[1] | CASE B AND 36/50[1] | CASE C AND 54/50[1] | CASE D AND 64/50[1] | CASE E | CASE F |
|---|---|---|---|---|---|---|
| TIME | 0955 | 1000 | 1015 | 1050 | 1115 | 1230 |
| SWELL DIRECTION (degrees true) | 330 | 320 | 300 | 300 | 300 | 300 |
| SWELL HEIGHT (feet) | 3-4 | 3-4 | 3-4 | 3-4 | 4-5 | 4-5 |
| WIND DIRECTION (degrees true) | 340 | 310 | 320 | 320 | 300 | 300 |
| WIND SPEED (knots) | 1-2 | 1-2 | 3-4 | 3-4 | 4-5 | 6-8 |
| SHIP HEADING (degrees true) | 340 | 310 | 295 | 300 | 300 | 300 |
| SHIP SPEED (knots) | 0 | 0 | .5 | 0 | 0 | 0 |
| WATER DEPTH (feet) | 120 | 120 | 96 | 120 | 136 | 180 |
| MAXIMUM SHIP ROLL (degrees) | 3-4 | 3-4 | 4-5 | 4-5 | 4-5 | 4-5 |
| MAXIMUM SHIP PITCH (degrees) | 2-3 | 2-3 | 2-3 | 2-3 | 3-4 | 3-4 |

[1]Represents pendulum weight (lbs) and S.A.E. oil weight number.

Figure 10. Hopkins Marine Station Research Vessel Proteus


Figure 11. Hopkins Marine Station Research Vessel Proteus Showing Location of Main Laboratory

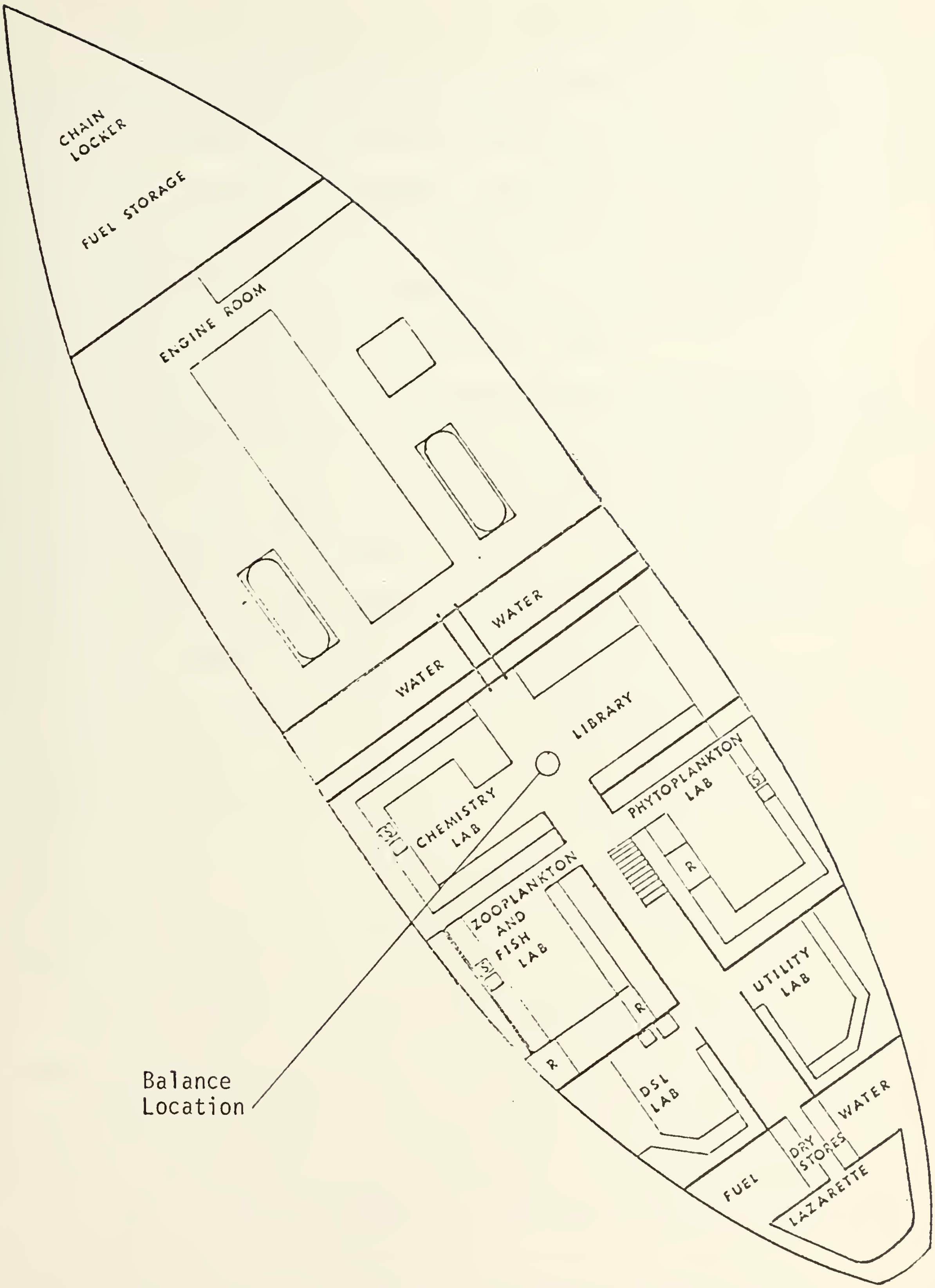


Figure 12. Hopkins Marine Station Research Vessel Proteus Showing Balance Location in Main Laboratory

The initial trial was made with the vessel proceeding at approximately ten knots with the seas broad on the starboard bow. The second trial was conducted with the ship proceeding at approximately three knots with the seas off the port quarter. The actual sea conditions for both trials are listed in Table VIII. Comparison of the results obtained indicate that the best measurements can be obtained when the vessel is parallel to the sea direction [Dehlinger, 1964].

Of the three vessels used in conducting the at-sea weighings, only the USNS BARTLETT (T-AGOR 14) was built as an oceanographic vessel from the keel up. This vessel is shown in Figure 13. Two of the three balance locations used are shown in Figure 14 and the other location is shown in Figure 15. The scientific office location was utilized in port to initially check the balances for proper operation.

Most of the weighings were conducted while the Bartlett was engaged in deep sea coring. Thus, at most times the was drifting slowly. Since the ship remained downwind of the coring cable to avoid tangling the cable in the screws, the waves were normally broadside. The vessel then was generally experiencing only rolling, side-swaying, and heaving motions [Korvin-Kroukorsky, 1961].

The wet laboratory location was on the vessel centerline, 6.6 feet above the mean water line, and at frame 56, which is 106.8 feet from the bow. The first platform location was again on the centerline, 2.0 feet above the mean water line, and at frame 40, which is 77.6 feet from the bow. Both positions are forward of the center of pitch using the 60-80 percent rule.

While making weighings at the first platform position the vessel was headed at first directly into the seas and later directly downseas.

TABLE VIII

SEA CONDITIONS ON 10 JUNE 1970

VESSEL: PROTEUS

| WEIGHING[1] | 18/10 | 36/10 | 54/10 | 64/10 | 18/50 | 36/50 | 54/50 | 64/50 |
|---|---|---|---|---|---|---|---|---|
| TIME | 0830 | 0900 | 0930 | 1015 | 1100 | 1145 | 1215 | 1230 |
| WAVE DIRECTION (degrees true) | 330 | 330 | 330 | 330 | 325 | 330 | 330 | 325 |
| SWELL DIRECTION (degrees true) | 330 | 330 | 330 | 330 | 330 | 335 | 330 | 340 |
| WAVE/SWELL HEIGHT (feet) | 0/2 | 0/2 | 0/2 | 1/3 | 2/4 | 2/4 | 3/5 | 3/6 |
| WIND DIRECTION (degrees true) | 320 | 320 | 325 | 320 | 330 | 330 | 335 | 330 |
| WIND SPEED (knots) | 2-4 | 2-4 | 6-8 | 8-10 | 8-10 | 8-10 | 12-14 | 15-17 |
| SHIP HEADING (degrees true) | 260 | 270 | 270 | 270 | 090 | 095 | 090 | 090 |
| SHIP SPEED (knots) | 10 | 10 | 10 | 10 | 2-3 | 2-3 | 2-3 | 2-3 |
| WATER DEPTH (fathoms) | 300 | 550 | 600 | 600 | 600 | 580 | 530 | 450 |
| MAXIMUM SHIP ROLL (degrees) | 3-4 | 3-4 | 3-4 | 3-4 | 5-6 | 5-6 | 5-6 | 5-6 |
| MAXIMUM SHIP PITCH (degrees) | 2-3 | 2-3 | 2-3 | 2-3 | 3-4 | 3-4 | 3-4 | 3-4 |

[1] Designated by pendulum weight (lbs) and S.A.E. oil weight number


Figure 13. USNS Bartlett Research Vessel

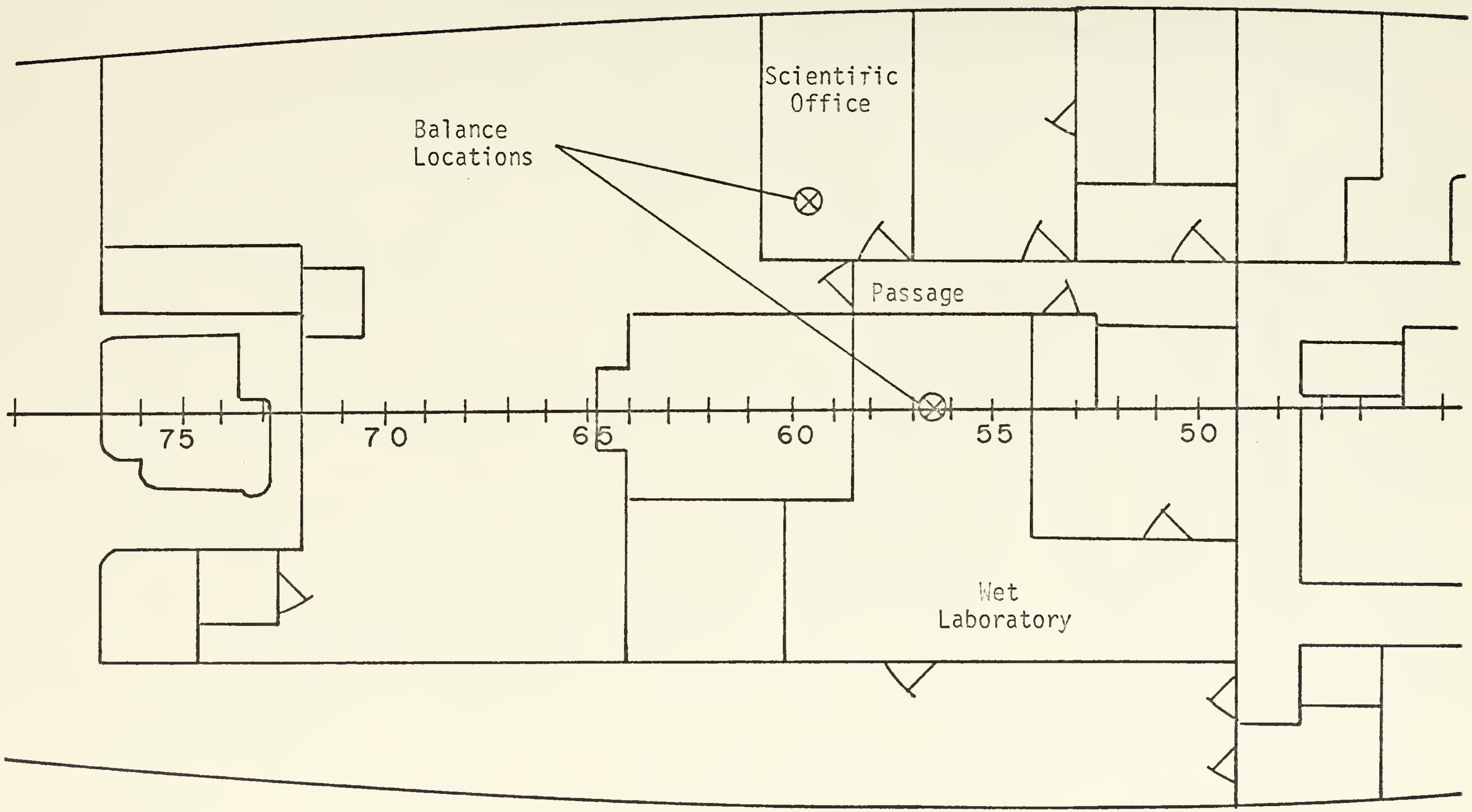


Figure 14. USNS Bartlett Main Deck Showing Two Balance Locations

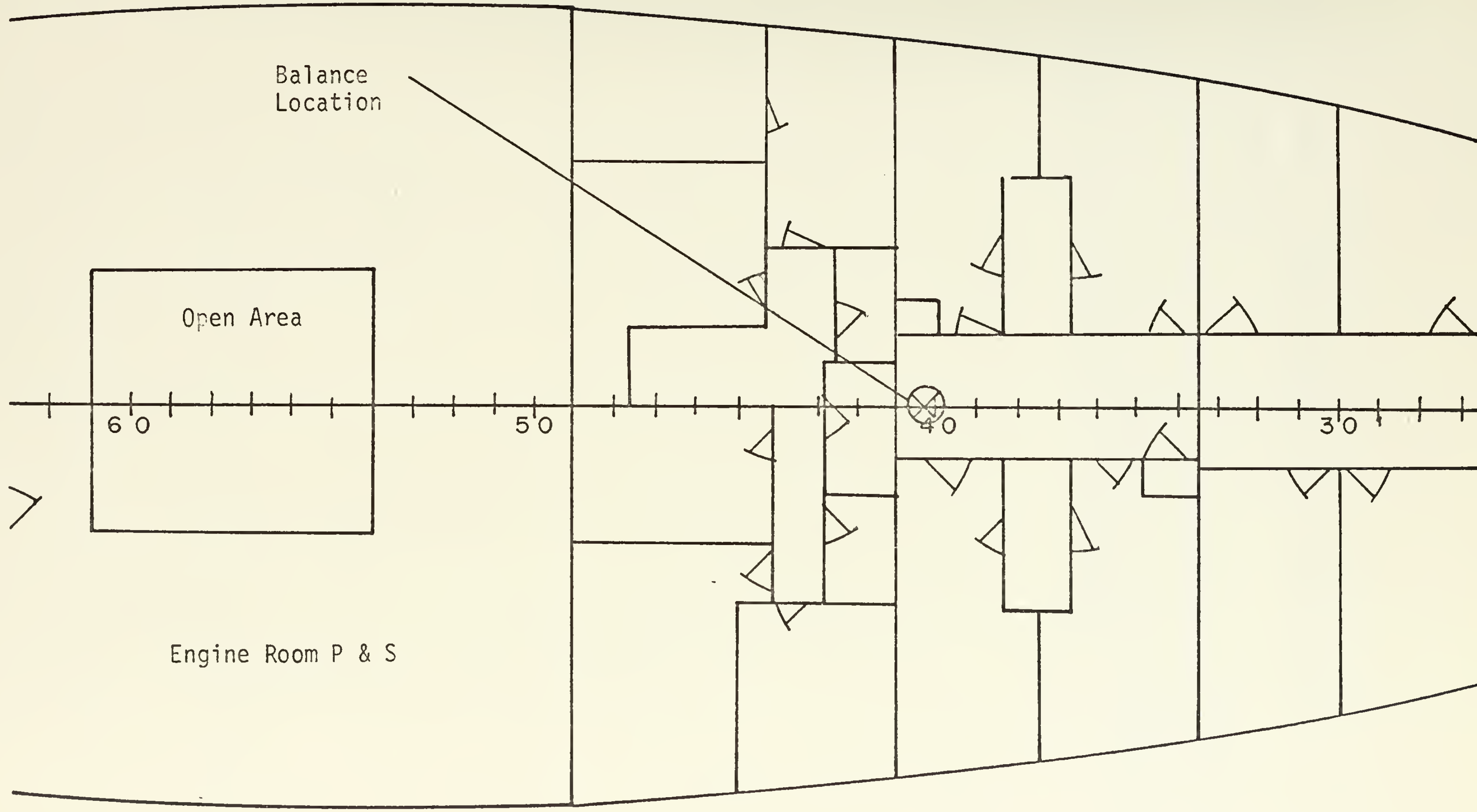


Figure 15. USNS Bartlett 1st Platform Showing Balance Location

However, time prohibited varying the oil and pendulum weight parameters while conducting these weighings. Sea conditions for all runs can be found in Table IX.

The BARTLETT has a designated gravimeter room located on the first platform at frame 47 off the centerline to port. This space was not available for use at the time of the sea trials.

TABLE IX

SEA CONDITIONS ON 22-24 APRIL 1970

VESSEL: BARTLETT

| WEIGHING | TRIAL 1 AND TRIAL 2 | 36/50 | 64/50 | 64/90 | TRIAL 4 | TRIAL 5 | TRIAL 6 | TRIAL 7 |
|---|---|---|---|---|---|---|---|---|
| DATE | 22 APRIL | 23 APRIL | 23 APRIL | 23 APRIL | 24 APRIL | 24 APRIL | 24 APRIL | 24 APRIL |
| TIME | 1400-1610 | 0943-1055 | 1230-1255 | 1512-1550 | 0910-0945 | 1300-1445 | 1510-1600 | 1605-1640 |
| WAVE DIRECTION (degrees true) | SHIP MOORED ALONGSIDE PIER. HARBOR SURGE PRESENT WITH A MAXIMUM SHIP ROLL OF 1-2 DEGREES. | 330 | 330 | 320 | 320 | 330 | 335 | 330 |
| SWELL DIRECTION (degrees true) | | 330 | 340 | 320 | 335 | 340 | 340 | 340 |
| WAVE/SWELL HEIGHT (feet) | | 3/4 | 3/4 | 3/5 | 4/6 | 5/7 | 4/8 | 4/8 |
| WIND DIRECTION (degrees true) | | 320 | 310 | 320 | 320 | 325 | 325 | 325 |
| WIND SPEED (knots) | | 12-13 | 10-12 | 14-15 | 17-18 | 19-20 | 19-20 | 19-21 |
| SHIP HEADING (degrees true) | | 228 | 200 | 225 | 230 | 225 | 310-325 | 125 |
| SHIP SPEED (knots) | | 0-.5 | 0-.5 | 0-.5 | 0-.5 | 0-.5 | 3-4 | 2-3 |
| WATER DEPTH (fathoms) | | 1800 | 1760 | 1800 | 1860 | 1860 | 1900 | 1900 |
| MAXIMUM SHIP ROLL (degrees) | | 4-6 | 4-6 | 4-5 | 5-6 | 6-7 | 4-5 | 3-4 |
| MAXIMUM SHIP PITCH (degrees) | | 1-2 | 2-3 | 2-3 | 4-5 | 3-4 | 6-7 | 4-5 |

## VII. PENDULUM MOTION

The mathematical analysis of the gimbal platform motion was done in two steps. The first step was to consider the two degrees of freedom, as shown in Figure 16, as two uncoupled rotations each with one degree of freedom, and without viscous dampening. The second step was to add viscous dampening to each rotation about the respective axes, A and B.

### A. UNDAMPENED FREE VIBRATION

Figure 17 illustrates the general configuration for the case of rotation about the B axis, while Figure 18 shows the characteristic dimension without the outer gimbal being included since it does not rotate about the B axis. The problem was thus reduced to a one degree of freedom system with pendulus motion in a free vibration mode without viscous dampening.

In conjunction with Figure 18 we have the following definitions:

$r_1$ = distance to the center of gravity of the inner gimbal,

$r_2$ = distance to the center of gravity of the pendulum and weight system,

$w_2$ = total weight below point 0 (pendulum rod and weights),

$w_1$ = total weight above point 0 (pendulum rod and inner gimbal,

$L$ = distance to the centroid of total weights,

$l$ = pendulum length,

$a_1$ = radius of lead weights,

$a_2$ = radius of pendulum shaft,

$h$ = height of weights,

$A$ = cross sectional area of pendulum rod,

$\gamma_s$ = specific weight of steel, and

$\gamma_L$ = specific weight lead.

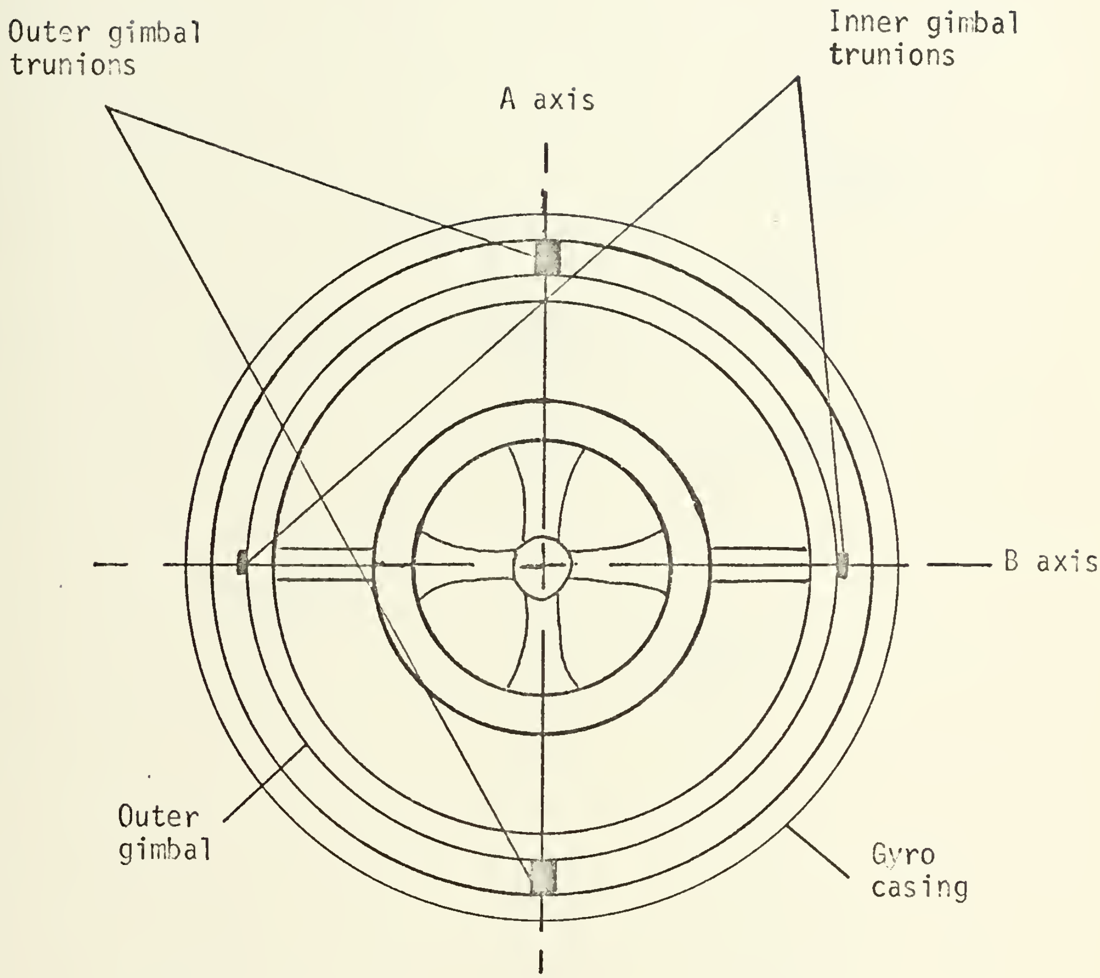


Figure 16. Gimbal Platform with Two Degrees of Freedom

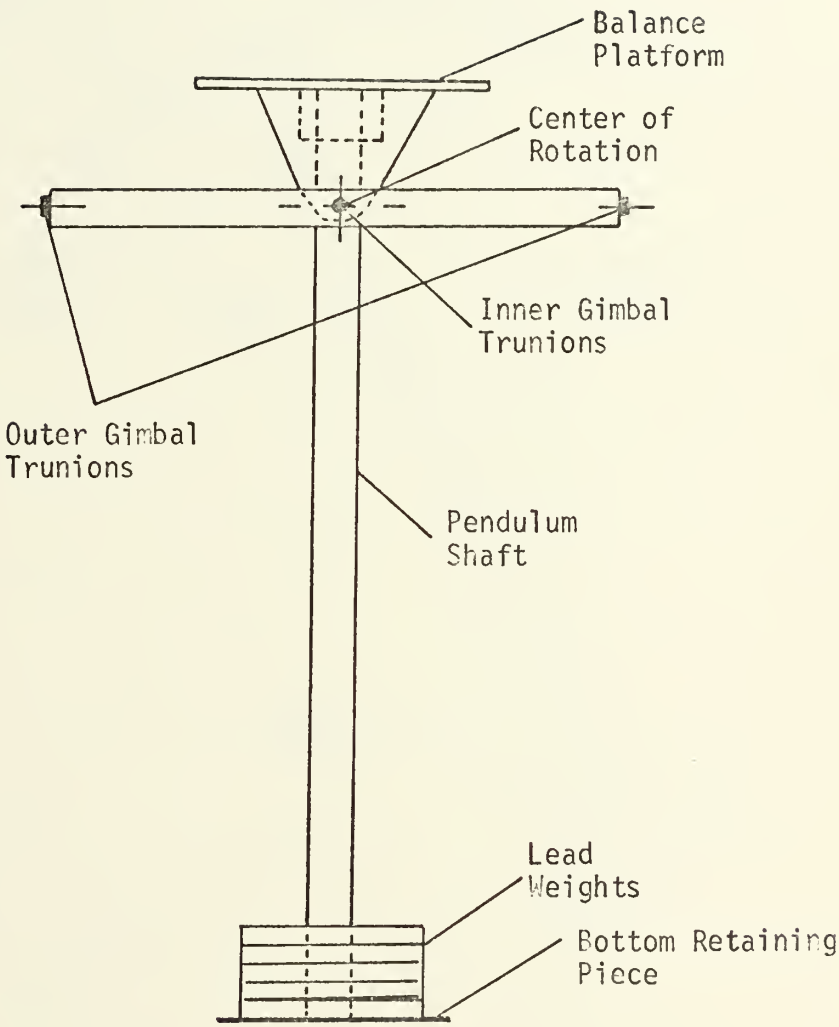


Figure 17. Rotation of the Gimbal Platform about the B Axis

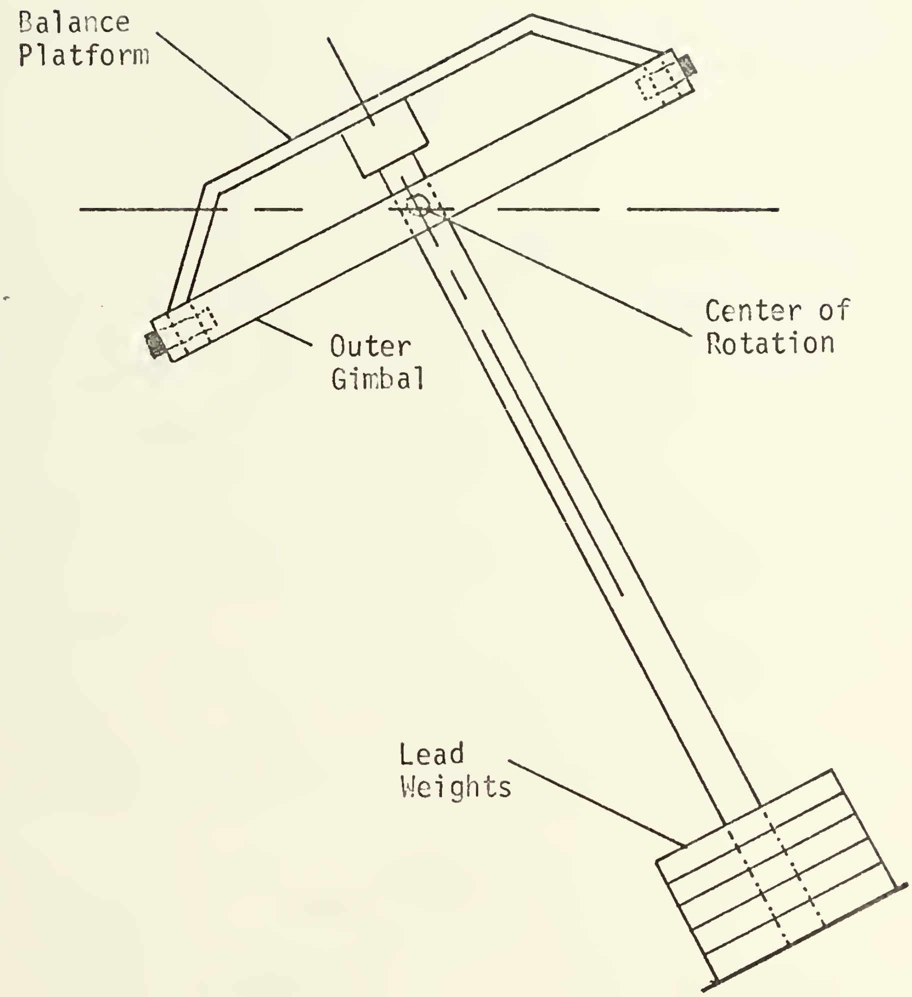


Figure 18. Characteristic Dimensions of Gimbal Platform

Of these quantities, the following are constant:

$r_1 = 5.88$ in,

$W_1 = 14.0$ lbs,

$l = 19.875$ in,

$a_1 = 3.0$ in,

$a_2 = 0.63$ in,

$A = 1.25$ in$^2$,

$\gamma_s = 0.283$ lbs/in$^3$, and

$\gamma_L = 0.41$ lbs/in$^3$ .

Except for $r_1$, $\gamma_s$, and $\gamma_L$ all these quantities were measured directly. The distance to the center of gravity of the inner gimbal, $r_1$ was determined experimentally while $\gamma_s$ and $\gamma_L$ were obtained from a materials handbook.

The remaining quantities; $r_2$, $W_2$, L, and h are dependent on the total weight used at the end of the pendulum. For the three different weight situations h, L, and $W_2r_2$ are listed in Table X, where $W_2r_2$ was computed from the equation:

$$W_2r_2 = \int r_2 dW_2 = (\gamma_s A l) \cdot 1/2 + (\gamma_c \pi a^2 h) \cdot L \quad . \tag{1}$$

Thus, the exact location of $r_2$ did not have to be determined.

TABLE X

PENDULUM VARIABLES

| CASE | PENDULUM WEIGHT (lbs) | h (in) | L (in) | $W_2r_2$ (in-lb) |
|---|---|---|---|---|
| I | 18 | 2.0 | 18.875 | 409.62 |
| II | 36 | 4.0 | 17.875 | 713.37 |
| III | 54 | 6.0 | 16.875 | 981.12 |

The equation of motion for a single degree of freedom pendulum, with free vibration, is given by the relation:

$$\begin{matrix}\text{Inertia} \\ \text{Moment}\end{matrix} = \begin{matrix}\text{Disturbing} \\ \text{Moment}\end{matrix} - \begin{matrix}\text{Restoring} \\ \text{Moment}\end{matrix} \quad .$$

For the case of zero disturbing moment this reduces to:

$$J_o \ddot{\theta} + W r_c \sin\theta = 0 \tag{2}$$

where $J_o$ is the polar mass moment of inertia of the system, $r_c$ is the distance to the center of gravity of the system, $\theta$ is the displacement angle, and $W$ is the weight of pendulum shaft and bob. The double dot indicates the second time derivative.

Applying this equation to the configuration of Figure 17 we obtain:

$$J_o \theta + (W_2 r_2 - W_1 r_1) \sin\theta = 0 \ . \tag{3}$$

$J_o$ can be determined through separate consideration of the portion of the assembly below the center of rotation and the portion of the assembly above the center of rotation (i.e., $J_o = J_1 + J_2$). Figure 19 shows the center of rotation for the system.

Because of the irregular shape of the inner gimbal, $J_1$ was determined experimentally. The period of oscillation of the inner gimbal was found by timing its free oscillation. The mass moment of inertia was then determined from the simple pendulum relationship

$$\omega = \sqrt{\frac{W_1 r_1}{J_1}} \tag{4}$$

Figure 19. Inner Gimbal With Pendulum and Weights Showing the B Axis of Rotation

where $\omega$ was found to be 7.42 $sec^{-1}$. Thus, $J_1$ becomes a constant for rotation about the B axis and is given as:

$$J_1 = \frac{W_1 r_1}{\omega^2} = \frac{(14.0)\ (5.88)}{(7.42)^2} = 1.495 \text{ in-lb-sec}^2 .$$

$J_2$, the mass moment of inertia of the lower pendulum rod and weights, was determined from the formula:

$$J_2 = \int r_2^{\,2} \frac{dW}{g} = \left[ \frac{1}{g} (\gamma_r A l) \frac{l^2}{3} + (\gamma_c \pi a^2 h) (L^2 + \frac{h^2}{12} + \frac{a_1^{\,2} + a_2^{\,2}}{4}) \right] \quad (5)$$

where the pendulum rod was considered to be a uniform thin rod, and the pendulum weights were considered to represent a hollow cylindrical shape placed around the pendulum rod.

Using Equation (5) for the three cases we obtain the respective inertia moments listed in Table XI.

TABLE XI

INERTIA MOMENTS FOR ROTATION ABOUT THE B AXIS

| CASE | $J_2$ | $J_1$ | $J_0$ |
|---|---|---|---|
| | ($in\text{-}lb\text{-}sec^2$) | | |
| I | 4.07 | 1.495 | 5.57 |
| II | 32.51 | 1.495 | 34.01 |
| III | 42.94 | 1.495 | 44.44 |

Setting $K = (W_2 r_2 - W_1 r_1)$ in Equation (3), where $W_1 r_1$ is a constant and equal to 82.32 in-lb for all cases, the values for K listed in Table XII were determined.

TABLE XII

RESTORING MOMENTS FOR ROTATION ABOUT THE B AXIS

| CASE | K (in-lb) |
|---|---|
| I | 327.30 |
| II | 631.05 |
| III | 898.80 |

With these values of $J_o$ and K, the respective natural frequencies of oscillations were computed for each case by letting $\sin\theta \cong \theta$ in equation (3) and solving for $\omega$ from $\omega = \sqrt{\frac{K}{J_o}}$ . Table XIII lists the natural frequencies of oscillation about the B axis.

TABLE XIII

NATURAL FREQUENCIES OF OSCILLATION ABOUT THE B AXIS

| CASE | $\omega$ ($sec^{-1}$) | f (cps) |
|---|---|---|
| I | 7.669 | 1.2206 |
| II | 4.308 | 0.6856 |
| III | 4.497 | 0.7158 |

For rotation about the A axis (see Figure 20) the only change required in the quantities determined previously for rotation about the B axis was that of the polar moment of inertia of the inner gimbal. The outer gimbal, which is symmetrical about a line perpendicular to the A axis and through the center of the system, does not contribute to any moments and consequently has no moment of inertia about the center of rotation.

By measuring the period of oscillation of the inner and outer gimbal about the A axis experimentally and utilizing equation (4), the moment

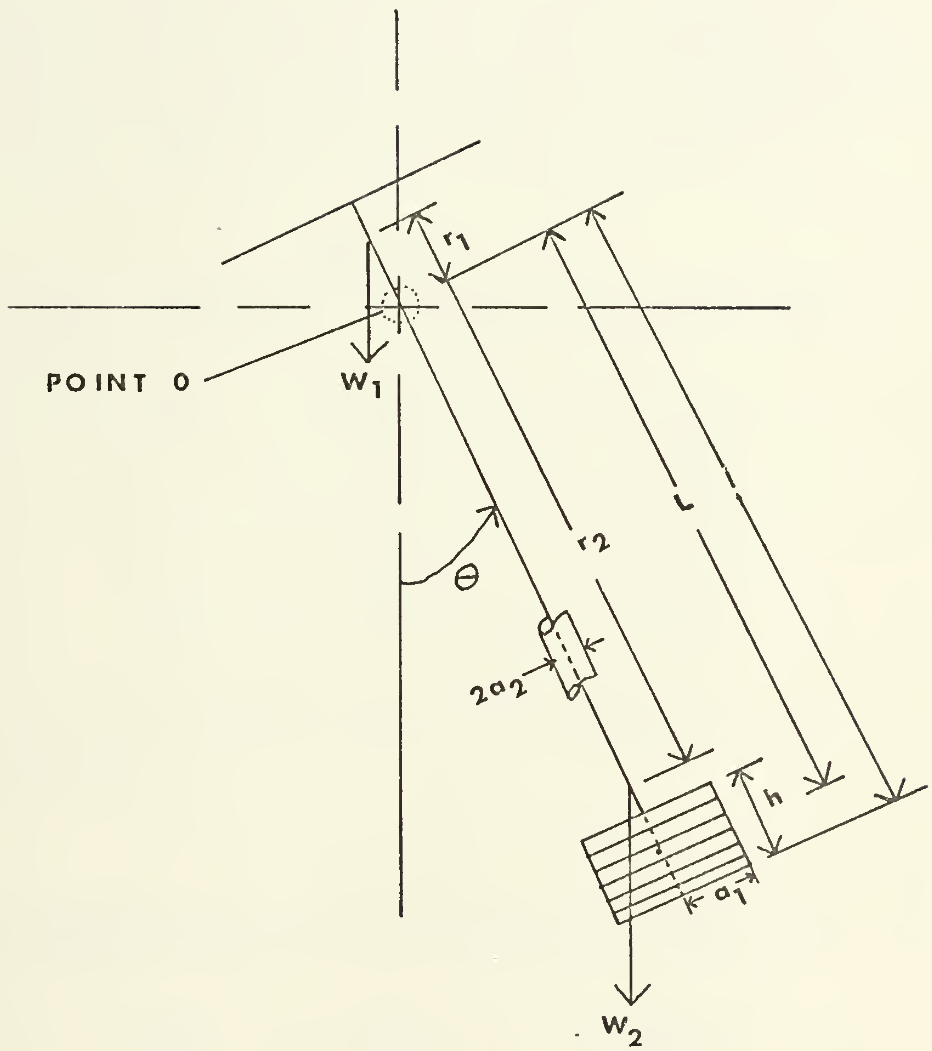


Figure 20. Rotation of the Gimbal Platform about the A Axis

of inertia was calculated to be:

$$J_1 = \frac{W_1 r_1}{\omega^2} = \frac{(14.0)\ (5.88)}{(3.778)^2} = 5.767\ (\text{in-lb-sec}^2)$$

where $\omega$ was found to be 3.778 $sec^{-1}$.

By computing a new $J_0$ and letting $\sin\theta \cong \theta$ in equation (3), the natural frequency of oscillation for each case was computed in the same manner as before. The results are listed in Table XIV.

TABLE XIV

NATURAL FREQUENCIES OF OSCILLATION ABOUT THE A AXIS

| CASE | $\omega$ ($sec^{-1}$) | f (cps) |
|---|---|---|
| I | 5.768 | 0.9180 |
| II | 4.060 | 0.6462 |
| III | 4.296 | 0.6837 |

Table XV summarizes the results of the independent pendulum rotation about axes A and B.

TABLE XV

NATURAL FREQUENCIES OF OSCILLATION ABOUT THE A AND B AXES

| CASE | A AXIS f (cps) | B AXIS f (cps) |
|---|---|---|
| I | 0.9180 | 1.2206 |
| II | 0.6462 | 0.6856 |
| III | 0.6837 | 0.7158 |

## B. DAMPENED FREE VIBRATION

In analyzing the effects of viscous dampening on the pendulus motion about the A and B axes, it was first necessary to determine the viscous-dampening coefficient, c. It was assumed that c was linear and proportional to the first power of the velocity [Tse, Morse, et al., 1964]. The units of the coefficient in a rotational system are in in-lb-sec. The single-degree-of-freedom system, with free vibrations and viscous-dampening, is given by

$$m\ddot{x} + c\dot{x} + Kx = 0 \tag{1}$$

where m is the mass of body, x is the linear displacement, c is the viscous dampening coefficient, and K is the spring constant. The three terms in the equation represent the inertia force, the dampening force, and the spring force. For rotational motion equation (1) can be written

$$J_o\ddot{\theta} + c\dot{\theta} + K\theta = 0 \ . \tag{2}$$

The solution of equation (2) involves a factor which diminishes with time, an oscillatory term for the vibration, and two constants of integration. The system's motion can be described as being either over-dampened, critically-dampened or under-dampened. The critically-dampened coefficient is given by $c_c = J_o\omega_n$ [Den Hartog, 1956].

A solution of the form

$$\theta = \theta_o e^{-bt} \cos pt \tag{3}$$

where the constant b and the damped natural frequency of oscillation p are defined as:

$$b = \frac{c}{2J_o} \tag{4}$$

$$p = \sqrt{\frac{K}{J_o} - \left(\frac{c}{2J_o}\right)^2} \tag{5}$$

satisfies equation (2) for all values of time with the phase angle of motion equal to zero. This result is plotted in Figure 21 and holds for all values of $\frac{K}{J_o} > (c/2J_o)^2$ , i.e. the under-damped case where $c = c_c$ . The combined results of a decreasing exponential factor and a sine wave is a "damped sine wave", lying in the space between the exponential curve and its mirror image.

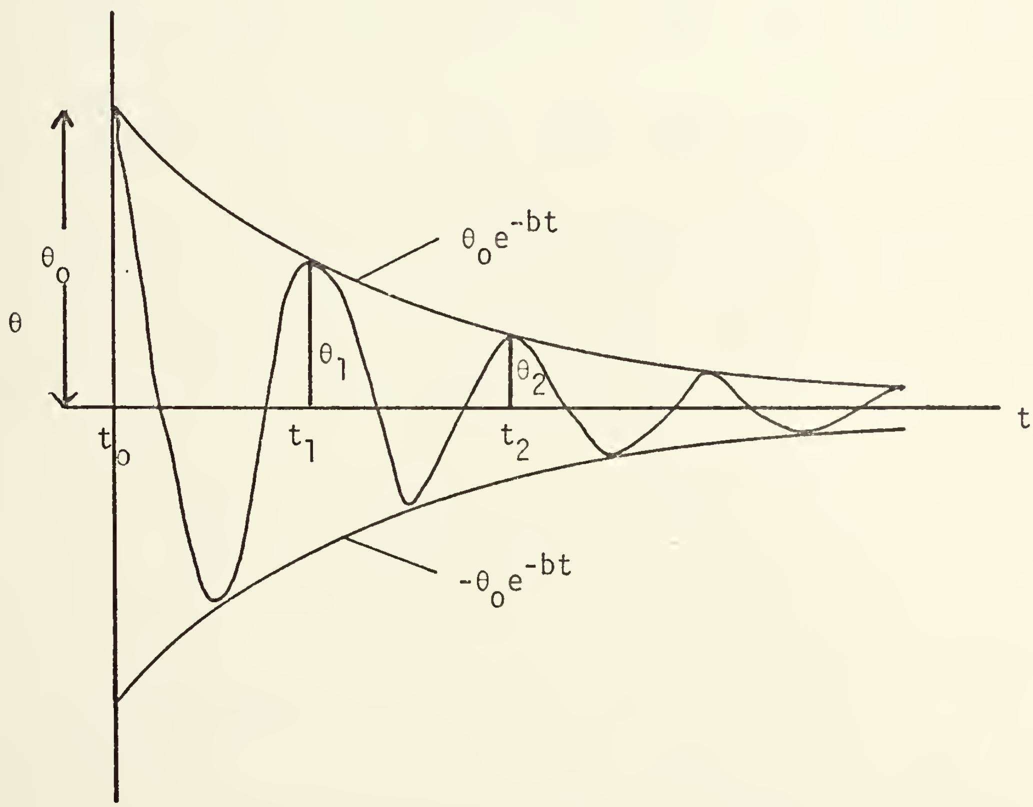


Figure 21. General Free Vibration Curve with Viscous Dampening

In order to determine the dampening constant, c, the oscillations of the pendulum were recorded on a constant speed movie camera for each axis of rotation under the different load conditions. From a knowledge of the camera speed (24 frames a second) the maximum left and right angular displacements were recorded as a function of time. The pendulum weight and dampening fluid used for each run are given in Table XVI and the respective curves are shown in Appendix C, with the data recorded in Appendix B.

TABLE XVI

PENDULUM WEIGHT AND VISCOUS FLUID COMBINATIONS USED IN DAMPENING THE MOTION

| RUN | 1 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|
| WEIGHT (lbs) | 18 | 18 | 36 | 54 | 18 | 36 | 54 |
| MEDIUM (Air or S.A.E. oil) | Air | 50W | 50W | 50W | 90W | 90W | 90W |

Measurement of successive maximum ordinate values at times $t_1$ and $t_2 = (t_1 + T)$, where T is the period of oscillation, gives $\theta_1 = \theta_o e^{-bt_1}$, and $\theta_2 = \theta_o e^{-(t_1 + T)}$ and their ratio

$$\frac{\theta_1}{\theta_2} = \frac{\theta_o e^{-bt_1}}{\theta_o e^{-b(t_1 + T)}} = e^{bT} . \tag{6}$$

The second ordinate is thus seen to be equal to the first multiplied by the factor $e^{-bT}$. This factor, which is smaller than unity, is the same for any two consecutive maxima and is independent of the amplitude of oscillation or of the time.

Taking the natural logarithm of each side of equation (6) gives

$$bT = \ln \frac{\theta_1}{\theta_2} \ . \tag{7}$$

The term bT is called the logarithmic decrement [Den Hartog, 1956].

Now for each of the vibration curves, $\theta_1$, $\theta_2$, and T were measured, b was calculated from (7), and c was calculated from (4). In order to eliminate possible errors due to small errors in establishing the zero displacement for each vibration curve, the total amplitude (left displacement + right displacement), between the exponential envelope was measured at successive maxima and used in equation (7). Table XVII is a tabulation of the period of oscillation (T), the logarithmic decrement (bT), and the viscous-dampening coefficient (c). Table XVIII is a comparison of the calculated natural frequencies with the observed or measured natural frequencies.

From Table XVII, it is seen that the viscous-dampening coefficient, c, is greater for the Z axis than for the B axis for respective weight/fluid combinations. This is accounted for by the presence of the two dash pots on the A axis as discussed in Section III and as shown in Figure 3. Once the outer gimbal rotations were less than approximately four and one half degrees, the gimbals failed to strike the piston dashpots and therefore failed to provide additional dampening.

From Table XVIII it is seen that the measured natural damped frequencies increase with increasing pendulum weight and decreasing fluid viscosity except between runs 7B and 10B. Since the viscosity of 90W oil is less than 50W oil, it can be concluded that the measured frequency

TABLE XVII

LOGARITHMIC DECREMENT AND VISCOUS DAMPENING COEFFICIENT VALUES

| | A AXIS | | | B AXIS | | |
|---|---|---|---|---|---|---|
| RUN | T (sec) | bT | c (in-lb-sec) | T (sec) | bT | c (in-lb-sec) |
| 1 | 1.58 | 0.0488 | 0.344 | 1.42 | 0.0278 | 0.218 |
| 5 | 1.77 | 0.4539 | 5.046 | 1.71 | 0.4806 | 3.113 |
| 8 | 1.75 | 0.4055 | 4.588 | 1.67 | 0.4290 | 2.862 |
| 6 | 1.68 | 0.4120 | 18.143 | 1.63 | 0.4187 | 17.155 |
| 9 | 1.66 | 0.3935 | 18.143 | 1.62 | 0.3735 | 15.583 |
| 7 | 1.63 | 0.4539 | 27.130 | 1.59 | 0.4125 | 23.064 |
| 10 | 1.62 | 0.4626 | 27.821 | 1.61 | 0.4055 | 22.389 |

of 10B should be greater than 7B. This inconsistency is the result of an incorrect data point in determining the logarithmic decrement.

The large differences between the measured and calculated natural frequencies of oscillation can be considered to be a result of the trunion bearing friction of each axis and the fact that the pendulum weights were not completely cylindrical. The slots were alternately parallel to the flow of motion as shown in Figure 2. This would increase the dampening factor and subsequently decrease the natural frequency of oscillation. Another reason for lower frequencies is that adjacent weights allowed oil to pass between them, creating a small dash pot effect.

As mentioned in Section IV, with this type of gimbal platform, where the center of rotation is below the balance platform, the moment created by the balance weight will subtract from the restoring moment thus increasing the time required to reach equilibrium after an initial pendulum displacement.

TABLE XVIII

DAMPENED NATURAL FREQUENCIES OF OSCILLATION
ABOUT THE A AND B AXES

| RUN | MEASURED (cps) | CALCULATED (cps) | MEASURED (cps) | CALCULATED (cps) |
|---|---|---|---|---|
| 1 | 0.6329 | 0.9180 | 0.7042 | 1.220 |
| 5 | 0.5650 | 0.9171 | 0.5814 | 1.219 |
| 8 | 0.5714 | 0.9164 | 0.5988 | 1.220 |
| 6 | 0.5952 | 0.6450 | 0.6024 | 0.6844 |
| 9 | 0.6024 | 0.6451 | 0.6135 | 0.6855 |
| 7 | 0.6135 | 0.6822 | 0.6289 | 0.7146 |
| 10 | 0.6173 | 0.6822 | 0.6211 | 0.7147 |

## VIII. RESULTS

Table XIX shows the total number of at-sea weighings made aboard the three research vessels. Of this total, 210 weighings were made on balance A, 24 on balance B, and the remaining number were made on the other balances listed in Table IV.

TABLE XIX

GENERAL SUMMARY OF AT-SEA WEIGHINGS

| DATE | VESSEL | NUMBER OF WEIGHINGS |
|---|---|---|
| 22-24 APRIL 1970 | BARTLETT | 50 |
| 15 MAY 1970 | NPS | 90 |
| 10 JUNE 1970 | PROTEUS | 63 |
| 13 JUNE 1970 | NPS | 44 |
| | TOTAL | 247 |

Because of the various operating requirements of the vessels, the weighings on 15 May 1970 represent the only sea trial where three fluids and three different weights per fluid were used with the vessel experiencing very nearly identical sea conditions throughout. Also, the ship was able to maintain the same heading with respect to the direction of seas during this period.

Figures 22, 23, and 24 show the weighing results of 15 May 1970 where pendulum weight is plotted versus sample weight for the 10W, 50W, and 90W fluids. It is apparent that the weights recorded for each pendulum weight are consistently influenced by the dampening medium to the same degree (with one exception) for each pendulum weight. Without

recording the specific weights obtained, Table XX illustrates the ordered arrangement of weights obtained by placing the dampening fluid number in its relative position about the actual sample weight line to indicate weight readings greater than or less than the actual weight.

TABLE XX

RELATIVE POSITIONS OF WEIGHT MEASUREMENTS MADE ON 15 MAY 1970 IN RELATION TO ACTUAL SAMPLE WEIGHT

| | | | |
|---|---|---|---|
| | | 10W | 50W |
| GREATER THAN ACTUAL WEIGHT | 90W | 50W | 90W |
| ----SAMPLE--WEIGHT---- | | | |
| LESS THAN ACTUAL WEIGHT | 50W | 90W | 10W |
| | 10W | | |
| Pendulum Weight (lbs) | 27 | 45 | 54 |

For each of the three pendulum weights one exception to the arrangement shown in Table XX was noted. Each exception was for a different sample weight as is shown in Table XXI.

Each sample was weighed ten times under different pendulum weight/ fluid combinations. In every instance the least per cent error of total sample weight recorded was that obtained with the 90W oil. The corresponding pendulum weights used were 27 pounds once, 45 pounds twice, and 64 pounds six times. The per cent error in total sample weight was always less than 0.10%. The weighing data is tabulated in Table XXII.

TABLE XXI

THREE EXCEPTIONS TO THE RELATIVE POSITIONS OF WEIGHT MEASUREMENTS MADE ON 15 MAY 1970

| | | | |
|---|---|---|---|
| GREATER | | | 50W |
| SAMPLE | 50W | 50W | 10W |
| WEIGHT | 0.074 | 2.947 | 5.342 |
| | 90W | 10W | 90W |
| LESS | 10W | 90W | |
| | 27 | 45 | 54 |
| | Pendulum Weight (lbs) | | |

Since the relative order of increasing viscosity magnitudes is 10W, 90W, 50W, Figures 22, 23, and 24, and Tables XX and XXI indicate that in general 10W oil under-dampens the pendulum motion, the 50W oil over-dampens the pendulum motion, and the 90W oil most nearly represents the desired critically dampened condition.

There appears to be no consistent correlation between the logarithmic decrements listed in Table XVII with the relative position of the weighings in different fluids as listed in Tables XX and XXI. It is seen that use of the 45 lb weight pendulum results in the greatest difference between the respective logarithmic decrements about the A and B axes and agrees in general with the greatest distance between the 50W and 90W curves (which appears at approximately the middle of the pendulum weight range) of Figures 22, 23, and 24.

Figures 25 and 26 show the weighing results of 10 June with 10W and 50W fluids and with the vessel on different headings for each trial. As a result of adverse weather the trials were suspended early in the

TABLE XXII

WEIGHING DATA[2] FROM BALANCE A ON 15 MAY 1970

VESSEL: NPS BALANCE LOCATION: WET LABORATORY[1]

| | STANDARD D[4] | ALONGSIDE PIER[5] | PENDULUM WEIGHT/DAMPENING OIL[3] 27/10 | 27/50 | 27/90 | 45/10 | 45/50 | 45/90 | 64/10 | 64/50 | 64/90 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE 14 | 0.074 | 0.072 | 0.059 | 0.079 | 0.065 | 0.082 | 0.081 | 0.065 | 0.059 | 0.092 | 0.075 |
| DIFFERENCE[6] | | -0.002 | -0.015 | +0.005 | -0.009 | +0.008 | +0.007 | -0.009 | -0.015 | +0.018 | +0.001 |
| ERROR (%) | | 2.70 | 20.27 | 6.76 | 12.16 | 10.81 | 9.46 | 12.16 | 20.27 | 24.32 | 1.35 |
| SAMPLE 12 | 0.213 | 0.214 | 0.190 | 0.209 | 0.215 | 0.251 | 0.238 | 0.209 | 0.177 | 0.240 | 0.219 |
| DIFFERENCE | | +0.001 | -0.023 | -0.004 | +0.002 | +0.038 | +0.025 | -0.004 | -0.036 | +0.027 | +0.006 |
| ERROR (%) | | 0.47 | 10.80 | 1.88 | 0.94 | 17.84 | 11.74 | 1.88 | 14.08 | 12.68 | 2.81 |
| SAMPLE 11 | 0.469 | 0.466 | 0.430 | 0.462 | 0.472 | 0.520 | 0.479 | 0.454 | 0.459 | 0.488 | 0.469 |
| DIFFERENCE | | -0.003 | -0.039 | -0.007 | +0.005 | +0.051 | +0.010 | -0.015 | -0.010 | +0.019 | 0.000 |
| ERROR (%) | | 0.64 | 8.32 | 1.50 | 1.07 | 10.87 | 2.13 | 3.20 | 2.13 | 4.05 | 0.00 |
| SAMPLE 9 | 1.679 | 1.680 | 1.648 | 1.667 | 1.675 | 1.732 | 1.688 | 1.665 | 1.662 | 1.685 | 1.675 |
| DIFFERENCE | | +0.001 | -0.031 | -0.012 | -0.004 | +0.053 | +0.009 | -0.014 | -0.017 | +0.006 | -0.004 |
| ERROR (%) | | 0.06 | 1.85 | 0.71 | 0.24 | 3.16 | 0.54 | 0.83 | 1.01 | 0.38 | 0.24 |
| SAMPLE 10 | 2.947 | 2.945 | 2.928 | 2.942 | 2.958 | 2.940 | 2.966 | 2.935 | 2.918 | 2.965 | 2.945 |
| DIFFERENCE | | -0.002 | -0.190 | -0.005 | +0.011 | -0.007 | +0.019 | -0.012 | -0.029 | +0.018 | -0.002 |
| ERROR (%) | | 0.07 | 0.64 | 0.17 | 0.37 | 0.24 | 0.64 | 0.41 | 0.98 | 0.61 | 0.07 |
| SAMPLE 5g[7] | 5.000 | 5.000 | 4.975 | 4.975 | 8 | 5.025 | 8 | 4.991 | 4.978 | 8 | 4.998 |
| DIFFERENCE | | 0.000 | -0.025 | -0.025 | | +0.025 | | -0.009 | -0.022 | | -0.002 |
| ERROR (5) | | 0.0 | 0.50 | 0.50 | | 0.50 | | 0.18 | 0.44 | | 0.04 |

TABLE XXII (Continued)

| | STANDARD D[4] | ALONGSIDE PIER[5] | 27/10 | 27/50 | 27/90 | 45/10 | 45/50 | 45/90 | 64/10 | 64/50 | 64/90 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE 8 | 5.342 | 5.342 | 5.310 | 5.332 | 5.351 | 5.362 | 5.346 | 5.339 | 5.349 | 5.360 | 5.310 |
| DIFFERENCE | | 0.000 | -0.032 | -0.010 | +0.009 | +0.020 | +0.004 | -0.003 | +0.007 | +0.018 | -0.032 |
| ERROR (%) | | 0.00 | 0.60 | 0.19 | 0.17 | 0.37 | 0.07 | 0.06 | 0.13 | 0.37 | 0.60 |
| SAMPLE 6 | 9.420 | 9.420 | 9.389 | 9.415 | 9.438 | 9.468 | 9.432 | 9.420 | 0.382 | 9.431 | 9.425 |
| DIFFERENCE | | 0.000 | -0.031 | -0.005 | +0.018 | +0.048 | +0.012 | 0.000 | -0.038 | +0.011 | +0.005 |
| ERROR (%) | | 0.00 | 0.33 | 0.05 | 0.19 | 0.51 | 0.13 | 0.00 | 0.40 | 0.12 | 0.05 |
| SAMPLE 3 | 84.882 | 84.861[9] | 84.818 | 84.860 | 84.895 | 84.942 | 84.878 | 84.878 | 84.875 | 84.905 | 84.883 |
| DIFFERENCE | | -0.021 | -0.064 | -0.022 | +0.013 | +0.060 | -0.004 | -0.004 | -0.009 | +0.023 | +0.001 |
| ERROR (%) | | 0.02 | 0.08 | 0.03 | 0.02 | 0.07 | 0.005 | 0.005 | 0.01 | 0.03 | 0.001 |

General: Ship's head 320°, speed 0-.5 knots. Wind from 330°, 2-5 knots. See Table VI.

Notes:
[1]See Figure 8.
[2]All weighings in grams.
[3]Pendulum weight in pounds, oil designated by S.A.E. Number.
[4]See Appendix A.
[5]64 pound pendulum weight and S.A.E. 90W oil used.
[6]Difference = STANDARD minus WEIGHING.
[7]Class S standard weight.
[8]Unable to weigh because 5.000 g range too high and 4.99 g range too low.
[9]Considered to be in error due to operator fatigue.

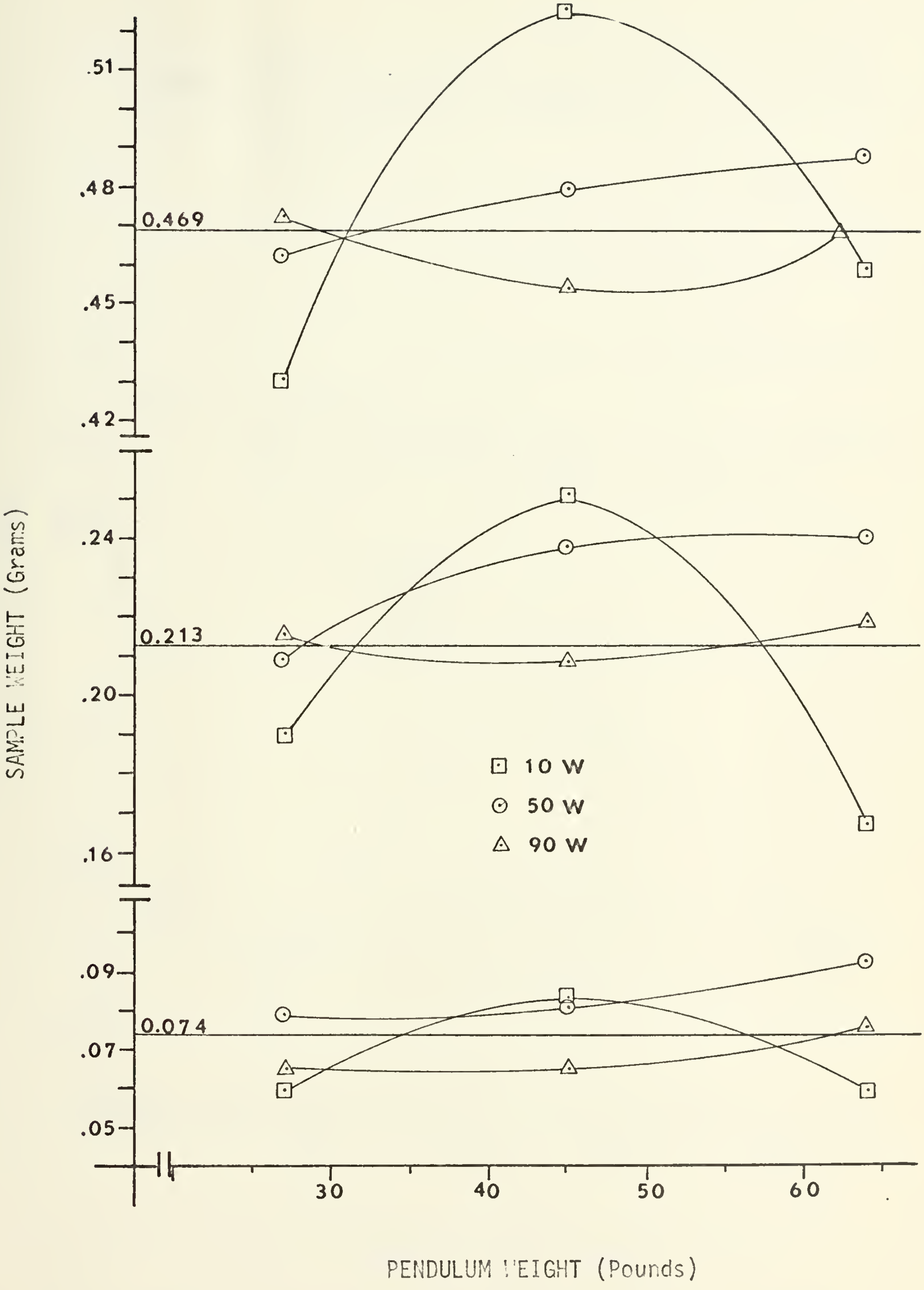


Figure 22. Variation in Weighings Obtained on 15 May in The Sample Weight Range of 0.074-0.469 Grams

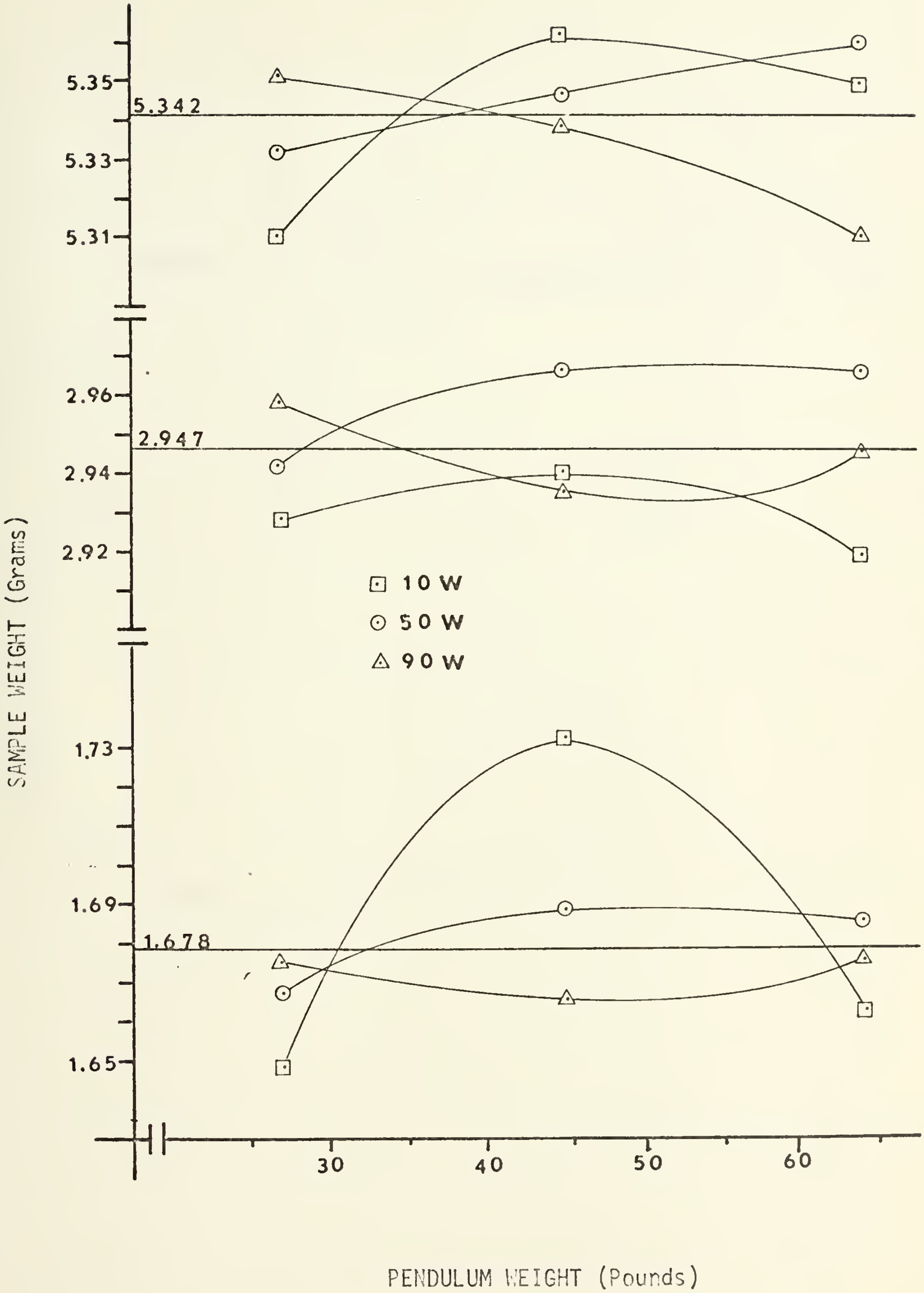


Figure 23. Variation in Weighings Obtained on 15 May in The Sample Weight Range of 1.679-5.342 Grams

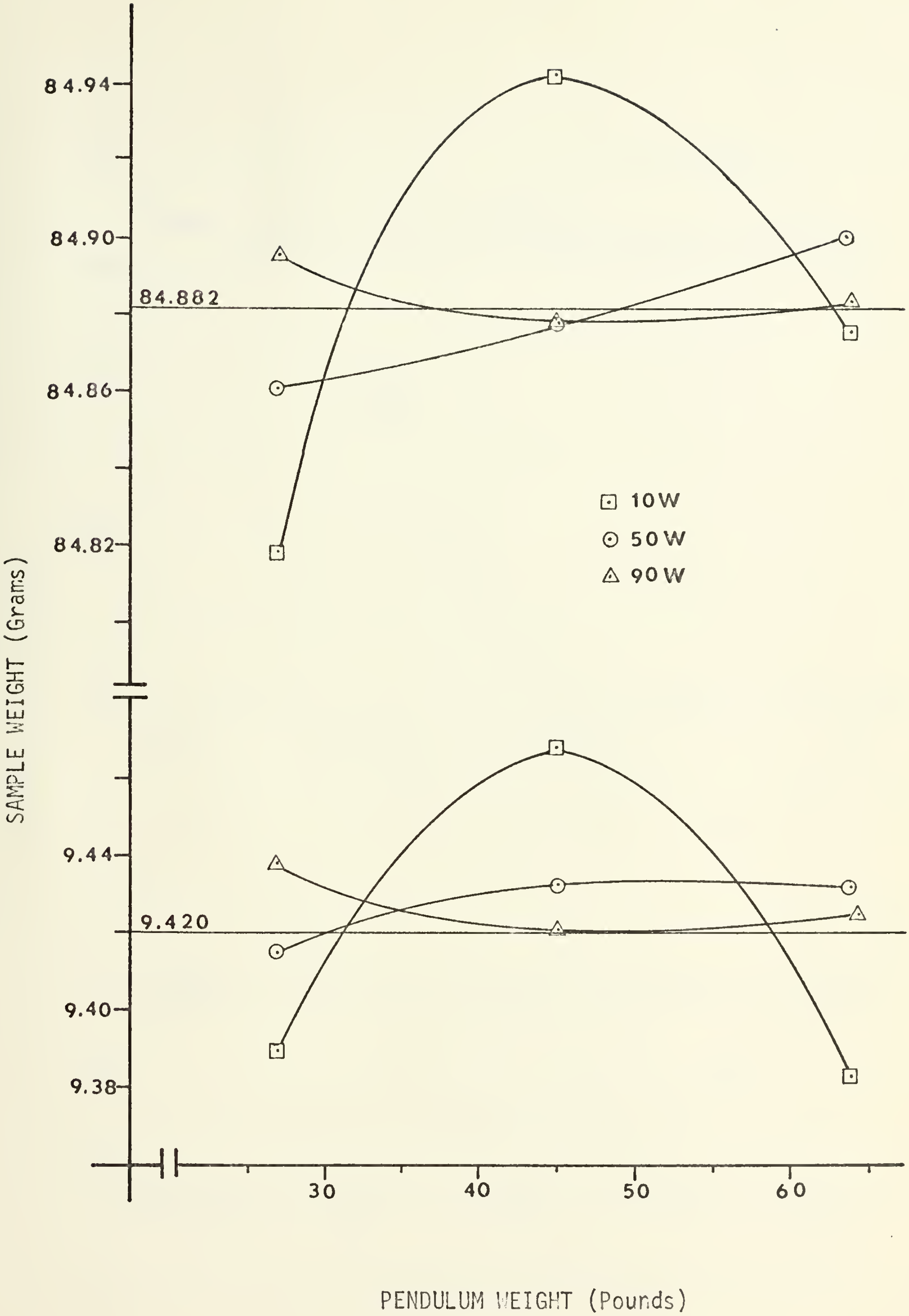


Figure 24. Variation in Weighings Obtained on 15 May in The Sample Weight Range of 9.420-84.87 Grams

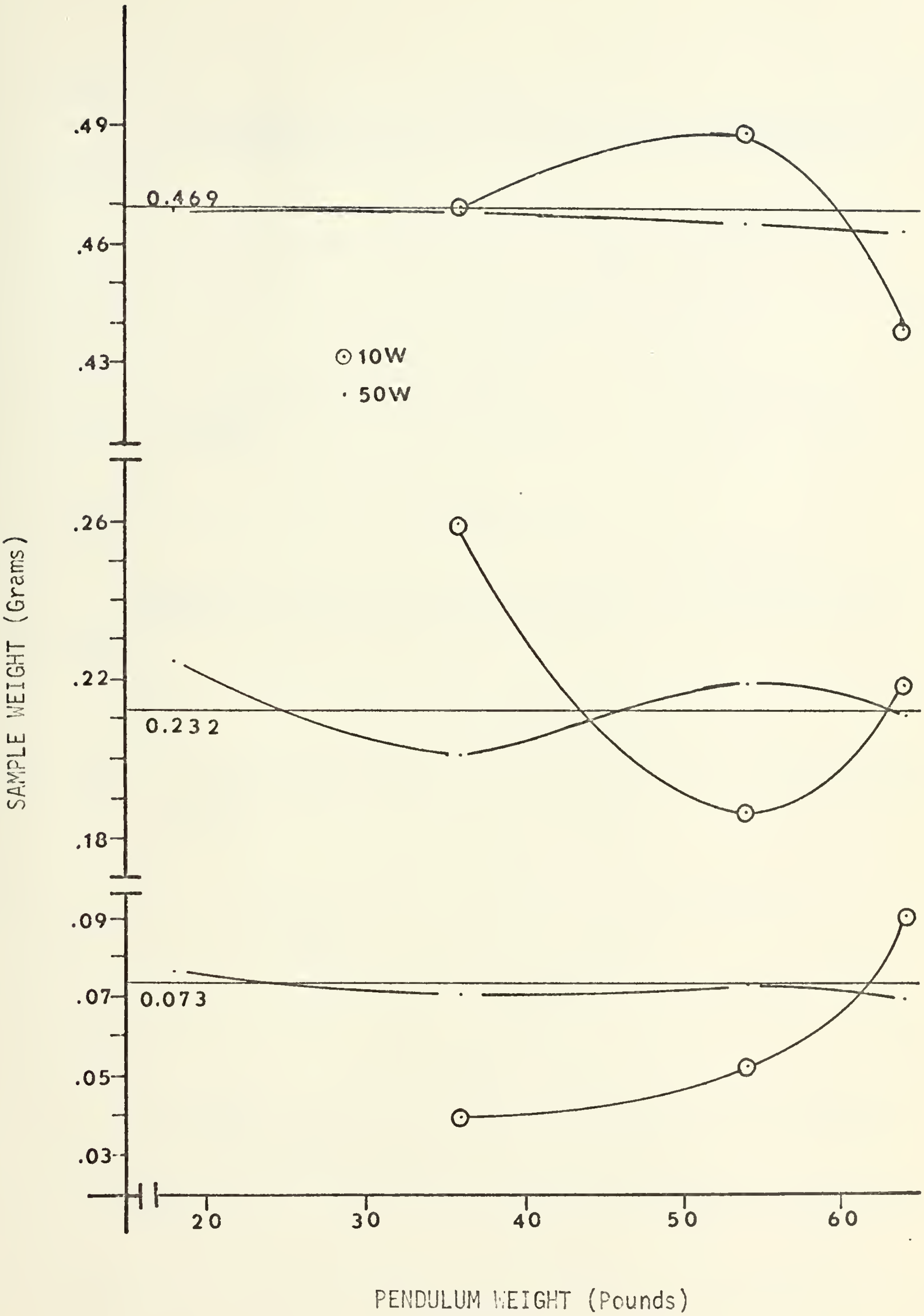


Figure 25. Variation in Weighings Obtained on 10 June in The Sample Weight Range of 0.073-0.469 Grams

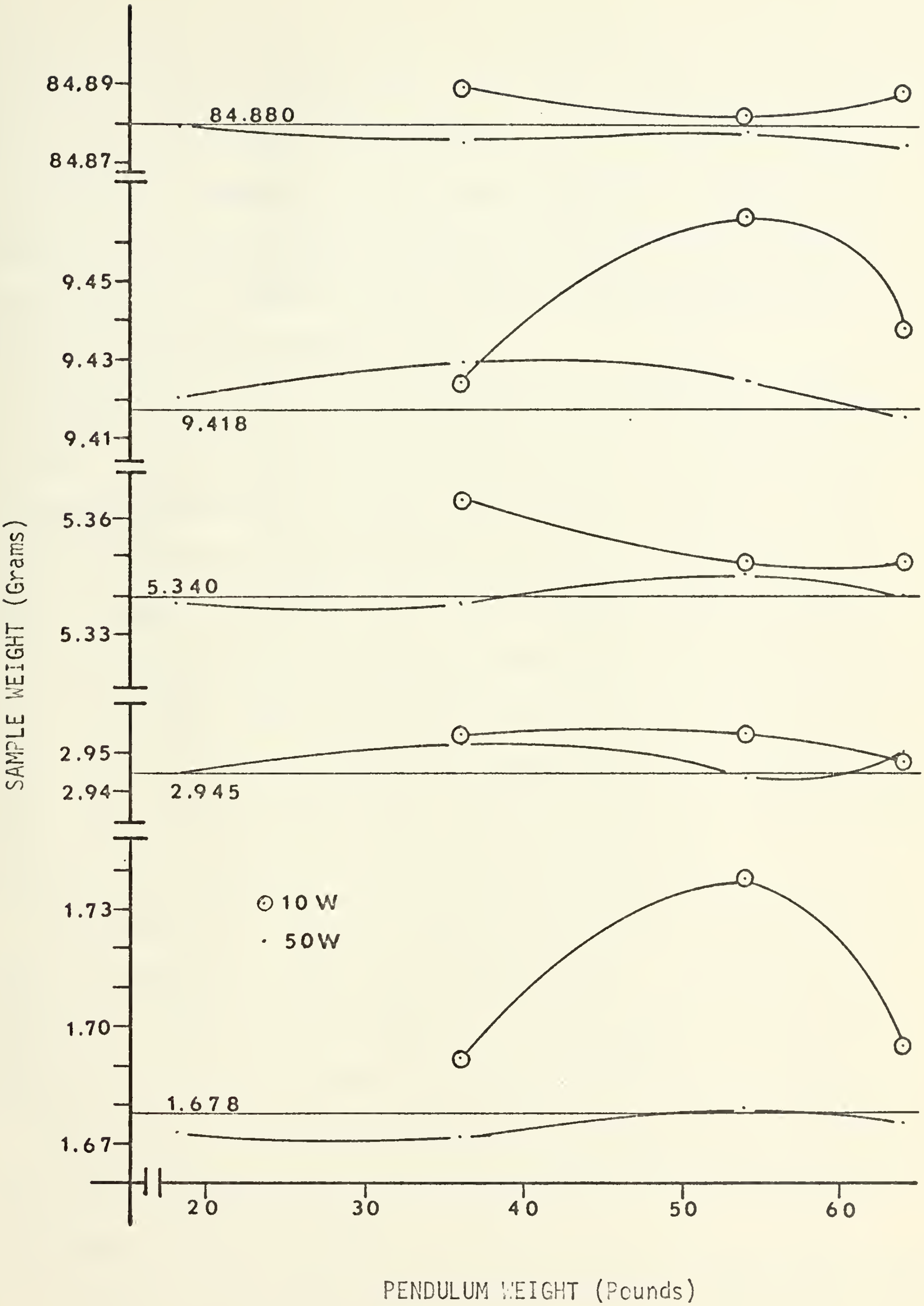


Figure 26. Variation in Weighings Obtained on 10 June in The Sample Weight Range of 1.678-84.88 Grams

afternoon without the 90W oil trial. The weighing data for the 10W and 50W oils is listed in Table XXIII. It is almost impossible to compare these results since each fluid represents a different ship heading and sea conditions. However, it can be seen that with the vessel heading parallel to the seas, (50W oil case), the results are more consistent and do not vary as widely as they do with the vessel heading almost directly into the seas (10W oil case).

Figure 27 shows the weighings obtained from a short sea trial on 13 July. At this time only the 50W fluid was used in order to compare the weight determination as a function of pendulum weight. The three sample weight ranges were approximately 10, 50, and 100 grams. This data is found in Table XXIV. It is seen that more consistent results were obtained with the 54 and 56 gram samples for all pendulum weights. The 10 gram sample shows a definite oscillation about the true weight from a high to a low to a high as the pendulum weight is increased. This suggests that with low sample weights the balance is more sensitive to the pendulum motion than with higher sample weights.

In addition to the results obtained with balance A, balance B was also evaluated on the same day by another person. The results are tabulted in Table XXV and a comparison between each Case (A-F), shows that the location of a balance and its beam orientation is important.

The results of the weighings made on 22-24 April have not been shown graphically because of the limited data points. The weighing data is tabulated in Tables XXVI-XXIX.

Table XVI shows again that the beam orientation is important. Trial 1 is with the beam balance awarthship and Trial 2 is with the beam fore and

TABLE XXIII

WEIGHING DATA[3] FROM BALANCE A ON 10 JUNE 1970

VESSEL: PROTEUS

BALANCE LOCATION: CENTER LINE 1ST PLATFORM[1]

| | STANDARD B[4] | 18/10[5] | PENDULUM WEIGHT/DAMPENING OIL[3] 36/10 | 54/10 | 64/10 | 18/50 | 36/50 | 54/50 | 64/50 |
|---|---|---|---|---|---|---|---|---|---|
| SAMPLE 14 | 0.073 | | 0.039 | 0.052 | 0.090 | 0.077 | 0.070 | 0.073 | 0.069 |
| DIFFERENCE[6] | | | -0.034 | -0.021 | +0.017 | +0.004 | -0.003 | 0.000 | -0.004 |
| ERROR (%) | | | 46.58 | 28.77 | 23.29 | 5.48 | 4.11 | 0.00 | 5.48 |
| SAMPLE 12 | 0.212 | | 0.259 | 0.186 | 0.218 | 0.225 | 0.205 | 0.219 | 0.211 |
| DIFFERENCE | | | +0.047 | -0.026 | +0.006 | +0.013 | -0.007 | +0.007 | -0.001 |
| ERROR (%) | | | 22.17 | 12.26 | 2.83 | 6.13 | 3.30 | 3.30 | 0.47 |
| SAMPLE 11 | 0.469 | | 0.469 | 0.488 | 0.438 | 0.468 | 0.469 | 0.465 | 0.463 |
| DIFFERENCE | | | 0.000 | -0.021 | -0.031 | -0.001 | 0.000 | -0.004 | -0.006 |
| ERROR (%) | | | 0.0 | 4.48 | 6.60 | 0.21 | 0.00 | 0.85 | 1.28 |
| SAMPLE 9 | 1.678 | | 1.692 | 1.738 | 1.695 | 1.673 | 1.672 | 1.680 | 1.675 |
| DIFFERENCE | | | +0.014 | +0.060 | +0.017 | -0.005 | -0.006 | +0.002 | -0.003 |
| ERROR (%) | | | 0.83 | 3.58 | 1.01 | 0.30 | 0.36 | 0.12 | 0.18 |
| SAMPLE 10 | 2.945 | | 2.954 | 2.955 | 2.948 | 2.944 | 2.952 | 2.943 | 2.950 |
| DIFFERENCE | | | +0.009 | +0.100 | +0.003 | -0.001 | +0.007 | -0.002 | +0.005 |
| ERROR (%) | | | 0.30 | 0.34 | 0.10 | 0.03 | 0.24 | 0.07 | 0.17 |
| SAMPLE 5g[7] | 4.998 | | 5.010 | 4.972 | 4.975 | 4.991 | 4.996 | 4.989 | 4.995 |
| DIFFERENCE | | | +0.012 | -0.026 | -0.023 | -0.007 | -0.002 | -0.009 | -0.003 |
| ERROR (%) | | | 0.24 | 0.52 | 0.46 | 0.14 | 0.10 | 0.18 | 0.06 |

TABLE XXIII (Continued)

| | STANDARD B[4] | 18/10[5] | 36/10 | 54/10 | 64/10 | 18/50 | 36/50 | 54/50 | 64/50 |
|---|---|---|---|---|---|---|---|---|---|
| SAMPLE 8 | 5.340 | | 5.364 | 5.349 | 5.349 | 5.338 | 5.338 | 5.346 | 5.340 |
| DIFFERENCE | | | +0.024 | +0.009 | +0.009 | -0.002 | -0.002 | +0.006 | 0.000 |
| ERROR (%) | | | 0.45 | 0.17 | 0.17 | 0.04 | 0.04 | 0.11 | 0.00 |
| SAMPLE 6 | 9.418 | | 9.424 | 9.467 | 9.439 | 9.420 | 9.429 | 9.425 | 9.416 |
| DIFFERENCE | | | +0.006 | +0.049 | +0.021 | +0.002 | +0.011 | +0.007 | -0.002 |
| ERROR (%) | | | 0.06 | 0.52 | 0.22 | 0.02 | 0.12 | 0.07 | 0.02 |
| SAMPLE 3 | 84.880 | | 84.889 | 84.882 | 84.889 | 84.879 | 84.875 | 84.878 | 84.875 |
| DIFFERENCE | | | +0.009 | +0.002 | +0.009 | -0.001 | -0.005 | -0.002 | -0.005 |
| ERROR (%) | | | 0.01 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.01 |

General: Weighings made with S.A.E. 10W oil were with ship on course 260°, spéed 10 knots. Wind from 320°, 6-8 knots. See Table VIII.

Weighings made with S.A.E. 50W oil were with ship on course 090°, speed 3 knots. Wind from 330°, 15-17 knots. See Table VIII.

Notes:

[1]See Figure 11.

[2]All weighings in grams.

[3]Pendulum weight in pounds and oil designated by S.A.E. Number.

[4]See Appendix A.

[5]Unable to zero balance accurately.

[6]Difference = STANDARD minus WEIGHING.

[7]Class S Standard Weight.

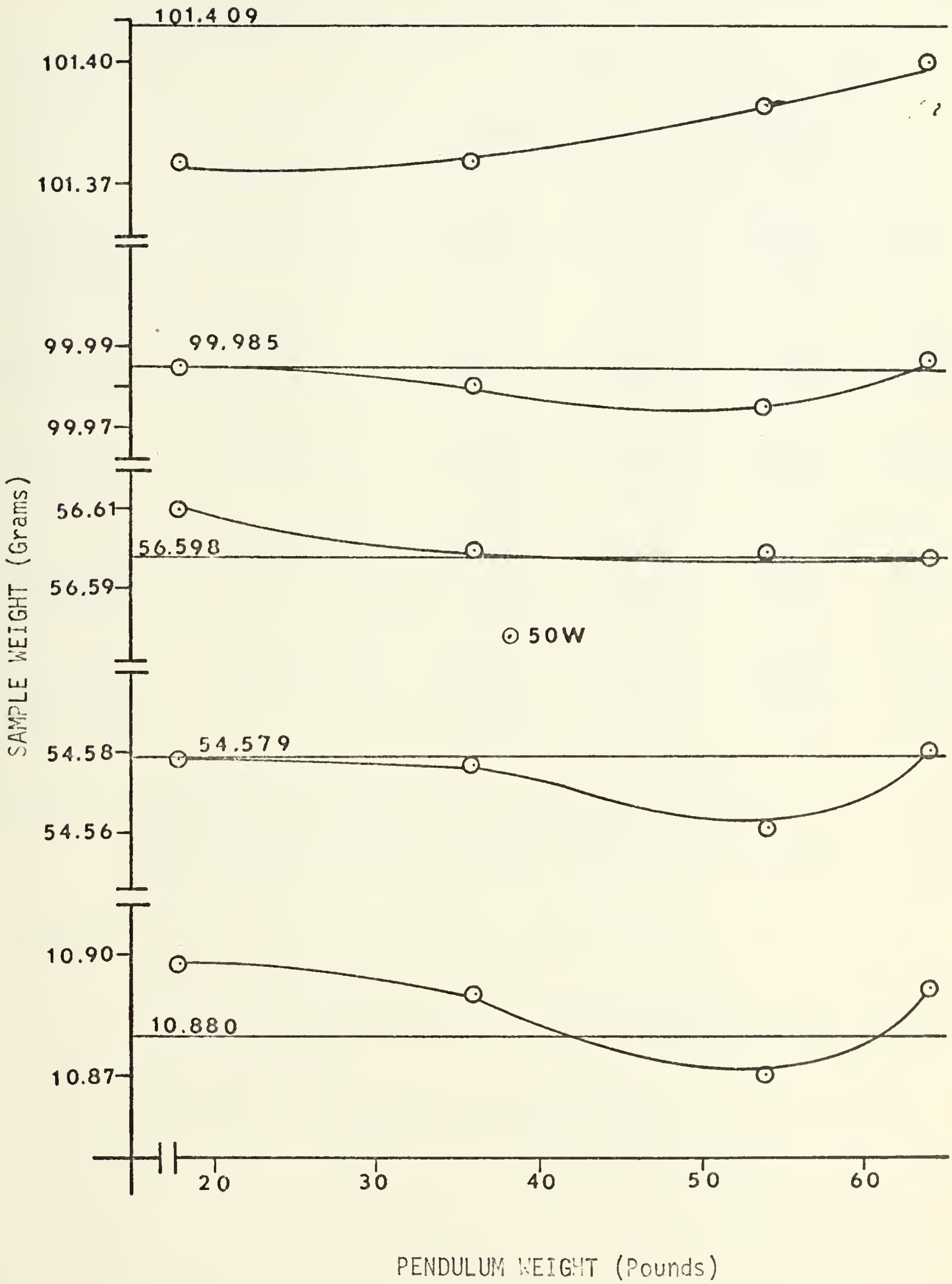


Figure 27. Variation in Weighings Obtained on 13 July as A Function of Pendulum Weight

TABLE XXIV

WEIGHING DATA[2] FROM BALANCE A ON 13 JULY 1970

VESSEL: NPS BALANCE LOCATION: WET LAB[1]

| | STANDARD J[4] | PENDULUM WEIGHT/DAMPENING OIL[3] 18/50 | 36/50 | 54/50 | 64/50 |
|---|---|---|---|---|---|
| SAMPLE A1 | 54.579 | 54.578 | 54.577 | 54.561 | 54.580 |
| DIFFERENCE[5] | | -0.001 | -0.002 | -0.018 | +0.001 |
| ERROR (%) | | 0.002 | 0.004 | 0.033 | 0.002 |
| SAMPLE A2 | 10.880 | 10.898 | 10.890 | 10.870 | 10.891 |
| DIFFERENCE | | +0.018 | +0.010 | -0.010 | +0.011 |
| ERROR (%) | | 0.165 | 0.091 | 0.091 | 0.101 |
| SAMPLE A3 | 101.409 | 101.375 | 101.375 | 101.389 | 101.400 |
| DIFFERENCE | | -0.036 | -0.034 | -0.20 | -0.009 |
| ERROR (%) | | 0.035 | 0.034 | 0.020 | 0.009 |
| SAMPLE A4 | 99.985 | 99.985 | 99.980 | 99.975 | 99.986 |
| DIFFERENCE | | 0.000 | -0.005 | -0.10 | +0.001 |
| ERROR (%) | | 0.021 | 0.002 | 0.002 | 0.000 |
| SAMPLE A5 | 56.598 | 56.610 | 56.599 | 56.599 | 56.598 |
| DIFFERENCE | | +0.012 | +0.001 | +0.001 | 0.000 |
| ERROR (%) | | 0.021 | 0.002 | 0.002 | 0.000 |

General: Weighings made with vessel maintaining station, ship head 310°-340° true, ship speed 0-.5 knots. Wind direction from 310°-340° true, speed 2-8 knots. See Table VII.

Notes:

[1]See Figures 8 and 9.

[2]Weights in grams.

[3]Pendulum weight in pounds, oil designated by S.A.E. number.

[4]See Appendix A.

[5]Difference = STANDARD minus WEIGHING.

## TABLE XXV

WEIGHING DATA[2] FROM BALANCE B ON 13 JULY 1970

VESSEL: NPS — BALANCE LOCATION: VARIOUS[1]

| | STANDARD G[3] | CASE A | CASE B | CASE C | CASE D | CASE E | CASE F |
|---|---|---|---|---|---|---|---|
| SAMPLE 14 | 0.0740 | 0.0906 | 0.0752 | 0.0755 | 0.0750 | 0.0745 | 0.0720 |
| DIFFERENCE[4] | | +0.0166 | +0.0012 | +0.0015 | +0.0010 | +0.005 | -0.0020 |
| ERROR (%) | | 22.43 | 1.62 | 2.03 | 1.35 | 6.76 | 2.70 |
| SAMPLE 12 | 0.2130 | 0.2272 | 0.2132 | 0.2092 | 0.2150 | 0.2110 | 0.2130 |
| DIFFERENCE | | +0.0142 | +0.0002 | -0.0038 | +0.0020 | -0.0020 | 0.000 |
| ERROR (%) | | 6.67 | 0.09 | 1.78 | 0.94 | 0.94 | 0.00 |
| SAMPLE 11 | 0.4714 | 0.4764 | 0.4694 | 0.4758 | 0.4690 | 0.4780 | 0.4660 |
| DIFFERENCE | | +0.0050 | -0.0020 | +0.0044 | -0.0024 | +0.0066 | -0.0014 |
| ERROR (%) | | 1.06 | 0.42 | 0.93 | 0.51 | 1.40 | 0.30 |

CASE A OFF CENTERLINE TO PORT IN PILOT HOUSE, BALANCE BEAM AWARTHSHIP
CASE B ON CENTERLINE IN PILOT HOUSE, BALANCE BEAM FORE AND AFT
CASE C ON CENTERLINE IN PILOT HOUSE, BALANCE BEAM FORE AND AFT
CASE D ON CENTERLINE IN PILOT HOUSE, BALANCE BEAM AWARTHSHIP
CASE E ON CENTERLINE IN WET LAB USING GIMBAL PLATFORM, BALANCE BEAM AWARTHSHIP, PENDULUM WEIGHT 64 POUNDS WITH S.A.E. 50W OIL.
CASE F ON CENTERLINE, IN WET LAB USING GIMBAL PLATFORM, BALANCE BEAM FORE AND AFT, PENDULUM WEIGHT 64 POUNDS WITH S.A.E. 50W OIL.

General: Ship's head 330°, 0-0.5 knots. Wind from 320°, 2-8 knots. See Table VII.

Notes:
[1] See case description above and Figures 8 and 9.
[2] Weights in grams.
[3] See Appendix A.
[4] Difference = STANDARD minus WEIGHING.

TABLE XXVI

WEIGHING DATA[3] FROM BALANCES A AND E ON 22 APRIL 1970

VESSEL: BARTLETT — BALANCE LOCATION: SCIENTIFIC OFFICE[2]

| | STANDARD A[4] | BALANCE TRIAL 1[5] | BALANCE TRIAL 2[6] | | STANDARD L[4] | BALANCE E |
|---|---|---|---|---|---|---|
| SAMPLE 14 | 0.073 | UNABLE TO MEASURE | 0.087 | SAMPLE 5g[8] | 5.00 | 5.00 |
| DIFFERENCE | | ---- | +0.014 | DIFFERENCE | | 0.00 |
| ERROR (%) | | ---- | 16.10 | ERROR (%) | | 0.00 |
| SAMPLE 12 | 0.210 | 0.125 | 0.225 | SAMPLE 6 | 6.45 | 6.53 |
| DIFFERENCE | | -0.085 | +0.015 | DIFFERENCE | | + .08 |
| ERROR (%) | | 40.48 | 7.14 | | | 1.23 |
| SAMPLE 10 | 2.945 | 2.849 | 2.960 | SAMPLE 1 | 22.20 | 22.00 |
| DIFFERENCE | | -0.096 | +0.015 | DIFFERENCE | | -0.20 |
| ERROR (%) | | 3.23 | 0.51 | ERROR (%) | | 0.90 |
| SAMPLE 5g[8] | 5.000 | 4.960 | 5.050 | SAMPLE 50g[8] | 50.00 | 50.00 |
| DIFFERENCE | | -0.040 | +0.050 | DIFFERENCE | | 0.00 |
| ERROR (%) | | 0.80 | 0.10 | ERROR (%) | | 0.00 |
| SAMPLE 6 | 6.469 | 6.445 | 6.470 | SAMPLE 2 | 64.96 | 65.00 |
| DIFFERENCE | | -0.024 | +0.001 | DIFFERENCE | | +0.04 |
| ERROR (%) | | 0.37 | 0.02 | ERROR (%) | | 0.06 |
| | | | | SAMPLE 15 | 147.61 | 147.58 |
| | | | | DIFFERENCE | | -0.03 |
| | | | | ERROR (%) | | 0.20 |

Notes: [1]Vessel moored alongside pier. Harbor surge present. Maximum ship roll 1-2 degrees.
[2]See Figure 14.
[3]Weights in grams.
[4]See Appendix A.
[5]Balance Beam Awarthships.
[6]Balance Beam Fore and Aft.
[7]Difference = STANDARD minus WEIGHING.
[8]Class S Standard Weights.

TABLE XXVII

WEIGHING DATA[3] FROM BALANCES D AND F ON 22 APRIL 1970

VESSEL: BARTLETT[1] BALANCE LOCATION: SCIENTIFIC OFFICE

| | STANDARD N[4] | BALANCE D | | STANDARD N[4] | BALANCE F |
|---|---|---|---|---|---|
| SAMPLE 50g [5] | 49.3 | 49.2 | SAMPLE 20g [5] | 20.00 | 20.10 |
| DIFFERENCE [6] | | -0.1 | DIFFERENCE [6] | | +0.10 |
| ERROR (%) | | 0.20 | ERROR (%) | | 0.50 |
| SAMPLE 4 | 150.6 | 150.6 | SAMPLE 2 | 64.97 | 65.04 |
| DIFFERENCE | | -0.3 | DIFFERENCE | | +0.07 |
| ERROR (%) | | 0.20 | ERROR (%) | | 0.11 |
| SAMPLE 16 | 293.3 | 293.5 | SAMPLE 5 | 188.60 | 188.65 |
| DIFFERENCE | | +0.2 | DIFFERENCE | | +0.05 |
| ERROR (%) | | 0.07 | ERROR (%) | | 0.03 |
| SAMPLE 17 | 416.9 | 417.2 | SAMPLE 16 | 295.09 | 295.15 |
| DIFFERENCE | | +0.3 | DIFFERENCE | | +0.06 |
| ERROR (%) | | 0.07 | ERROR (%) | | 0.02 |
| | | | SAMPLE 16 + 17 | 713.26 | 713.15 |
| | | | DIFFERENCE | | -0.11 |
| | | | ERROR (%) | | 0.02 |

Notes: [1]Vessel moored alongside pier. Harbor surge present. Maximum ship roll 1-2 degrees.

[2]See Figure 14.

[3]Weights in grams.

[4]See Appendix A.

[5]Class S standard weight.

[6]Difference = STANDARD minus WEIGHING.

TABLE XXVIII

WEIGHING DATA[2] FROM BALANCE A ON 23-24 APRIL 1970

VESSEL: BARTLETT

BALANCE LOCATION: WET LABORATORY AND FIRST PLATFORM [1]

| | STANDARD A[3] | TRIAL 3[4] PENDULUM WEIGHT/DAMPING OIL[6] | | | | TRIAL 4[5] |
|---|---|---|---|---|---|---|
| | | 36/50 | 64/50 | 64/90 | 64/90[7] | 64/90 |
| SAMPLE 14 | 0.073 | | | 0.079 | 0.075 | |
| DIFFERENCE[8] | | | | +0.006 | +0.003 | |
| ERROR (%) | | | | 8.22 | 4.10 | |
| SAMPLE 12 | 0.210 | 0.205 | 0.209 | | | 0.218 |
| DIFFERENCE | | -0.005 | -0.001 | | | +0.008 |
| ERROR (%) | | 2.38 | 0.48 | | | 3.8 |
| SAMPLE 11 | 0.467 | | | | 0.466 | |
| DIFFERENCE | | | | | -0.001 | |
| ERROR (%) | | | | | 0.21 | |
| SAMPLE 10 | 2.945 | | 2.949 | 2.948 | 2.950 | 2.950 |
| DIFFERENCE | | | +0.004 | +0.003 | +0.005 | +0.005 |
| ERROR (%) | | | 0.14 | 0.10 | 0.17 | 0.17 |
| SAMPLE 5g[9] | 5.000 | 5.000 | | | | |
| DIFFERENCE | | 0.000 | | | | |
| ERROR (%) | | 0.00 | | | | |
| SAMPLE 8 | 5.340 | 5.325 | 5.342 | 5.340 | | 5.340 |
| DIFFERENCE | | -0.015 | +0.002 | 0.000 | | 0.000 |
| ERROR (%) | | 0.28 | 0.04 | 0.00 | | 0.00 |
| SAMPLE 6 | 6.469 | 6.462 | | | 6.470 | 6.475 |
| DIFFERENCE | | -0.007 | | | -0.001 | +0.006 |
| ERROR (%) | | 0.11 | | | 0.02 | 0.09 |

Notes: [1]See Figures 14 and 15.

[2]Weighings in grams.

[3]See Appendix A

[4]Centerline, main deck wet laboratory. See Figure 14.

[5]Centerline, first platform. See Figure 15.

[6]Pendulum weights in pounds, oil designated by S.A.E. Number.

[7]Personnel Code 4.

[8]Difference = STANDARD minus WEIGHING.

[9]Class S standard weight.

TABLE XXIX

WEIGHING DATA[2] FROM BALANCE B ON 24 APRIL 1970

VESSEL: BARTLETT

BALANCE LOCATION: CENTER LINE FIRST PLATFORM[1]

| | STANDARD K [3] | TRIAL 5 | TRIAL 6 | TRIAL 7 |
|---|---|---|---|---|
| SAMPLE 1mg[4] | 1.02 | 1.12 | 1.06 | 1.04 |
| DIFFERENCE[5] | | +0.10 | +0.04 | +0.02 |
| ERROR (%) | | 9.80 | 3.92 | 1.96 |
| SAMPLE 10mg | 10.06 | 10.06 | 9.98 | 9.96 |
| DIFFERENCE | | 0.00 | -0.08 | -0.10 |
| ERROR (%) | | 0.00 | 0.80 | 0.99 |
| SAMPLE 10mg | 10.06 | 10.12 | | |
| DIFFERENCE | | +0.06 | | |
| ERROR (%) | | 0.59 | | |
| SAMPLE 20mg | 20.06 | 20.00 | 20.08 | 20.10 |
| DIFFERENCE | | -0.06 | +0.02 | +0.04 |
| ERROR (%) | | 0.30 | 0.10 | 0.20 |
| SAMPLE 14 | 73.76 | | 71.44 | 73.38 |
| DIFFERENCE | | | -2.32 | -0.38 |
| ERROR (%) | | | 3.15 | 0.52 |
| SAMPLE 14 | 73.76 | | 74.34 | |
| DIFFERENCE | | | +0.58 | |
| ERROR (%) | | | 0.79 | |

General: All weighings made with 64 pounds pendulum weight and S.A.E. 90W oil. See Table IX for sea conditions.

Notes:

[1]See Figure 15.

[2]Weights in milligrams.

[3]See Appendix A.

[4]Class M calibration weight.

[5]Difference = STANDARD minus WEIGHING.

aft. Therefore, the balance beam should be orientated appropriately depending on which degree of freedom (roll or pitch) is experiencing the greatest rotation.

In Table XXIX, Trial 5 was with the seas on the beam, Trial 6 was directly into the seas, and Trial 7 was directly down seas. From the few data points, it can be seen that the weighings during Trial 7 more closely approach the true sample weight and have less of a range of percent error than do Trials 5 and 6.

Table XXX tabulates the maximum and minimum percentages of error in total sample weight for all weigh-ins. It is seen that the differences between actual sample weight and the observed values is approximately a constant, and therefore, the percent error decreases with an increased sample size.

TABLE XXX

PERCENT ERROR IN SAMPLE WEIGHINGS

| BALANCE A | | | BALANCE B | | |
|---|---|---|---|---|---|
| SAMPLE WEIGHT (gram) | MAXIMUM ERROR (%) | MINIMUM ERROR (%) | SAMPLE WEIGHT (gram) | MAXIMUM ERROR (%) | MINIMUM ERROR (%) |
| 0.073 | 46.58 | 0.00 | 0.0740 | 22.43 | 0.52 |
| 0.212 | 22.17 | 0.47 | 0.2130 | 6.67 | 0.00 |
| 0.469 | 10.87 | 0.00 | 0.4714 | 1.40 | 0.30 |
| 1.679 | 3.58 | 0.12 | 0.001 | 9.80 | 1.96 |
| 2.947 | 1.73 | 0.03 | 0.010 | 0.99 | 0.00 |
| 5.000 | 0.52 | 0.00 | 0.020 | 0.30 | 0.10 |
| 5.340 | 0.60 | 0.00 | | | |
| 6.469 | 0.37 | 0.02 | | | |
| 9.420 | 0.52 | 0.00 | | | |
| 10.882 | 0.18 | 0.07 | | | |
| 54.579 | 0.03 | 0.00 | | | |
| 56.604 | 0.02 | 0.00 | | | |
| 84.880 | 0.01 | 0.00 | | | |
| 101.409 | 0.04 | 0.01 | | | |
| 101.990 | 0.02 | 0.00 | | | |

## IX. CONCLUSIONS

The use of a two degree of freedom gimbal platform, with damped motion, enables certain standard laboratory balances to operate satisfactorily at sea under varying sea conditions.

The gimbal apparatus must be placed on board the vessel such that the vessel motions will have a minimal effect on the gimbal platform and in turn on the laboratory balance. The vessel centerline and center of pitch provide the best position.

The ship on which the gimbal platform is to be used must position itself such that its motions and associated accelerations are at a minimum. The ship's maximum speed while using the gimbal platform, will depend on the prevalent sea conditions. However, a course parallel to the direction of seas is the most advantageous in determining weight measurements at sea.

The gimbal platform should have removable pendulum bob weights and should be constructed so that the balance platform is at a minimum distance from the center of rotation. Removable weights and a means to lengthen or shorten the pendulum rod will allow for a change in the natural damped frequency of the apparatus.

Balances to be used at sea should not operate on a fulcrum point or knife edge principle. The balance should have internal viscous dampening and present a mechanical readout. The balance should be corrosion resistant, have a small degree of internal compensation for out of level conditions, be shielded from air currents, and should be as light as possible to exclude additional external forces from influencing the pendulum motion.

## APPENDIX A

## WEIGHT STANDARDS[1]

| STANDARD | BALANCE USED | DATE WEIGHTED | PERSONNEL CODE |
|---|---|---|---|
| A | A | 28 APRIL 1970 | 1 |
| B | A | 9 JUNE 1970 | 1 |
| C | A | 6 JULY 1970 | 1 |
| D | A | 18 MAY 1970 | 1 |
| E | A | 22 MAY 1970 | 4 |
| F | B | 28 APRIL 1970 | 1 |
| G | B | 14 JULY 1970 | 1 |
| H | B | 13 JULY 1970 | 3 |
| I | C | 12 JULY 1970 | 2 |
| J | A | 4 AUGUST 1970 | 1 |
| K | B | 28 APRIL 1970 | 1 |
| L | E | 28 APRIL 1970 | 1 |
| M | D | 28 APRIL 1970 | 1 |
| N | F | 28 APRIL 1970 | 1 |

[1]All Standards were weighed on a laboratory table except for STANDARD H which was weighed on NPS Vessel while in port.

APPENDIX B

PENDULUM DAMPENING DATA

| RUN | DISPLACEMENT (Degrees) L | DISPLACEMENT (Degrees) R | TIME (Seconds) | RUN | DISPLACEMENT (Degrees) L | DISPLACEMENT (Degrees) R | TIME (Seconds) |
|---|---|---|---|---|---|---|---|
| 1A | 12.9 | | 0.00 | 1B | 13.2 | | 0.00 |
| | | 12.0 | 0.83 | | | 11.6 | 0.75 |
| | 11.9 | | 1.67 | | 11.3 | | 1.46 |
| | | 11.3 | 2.42 | | | 11.2 | 2.21 |
| | 11.0 | | 3.21 | | 10.2 | | 24.33 |
| | | 10.5 | 3.96 | | | 10.0 | 25.04 |
| | 9.0 | | 11.13 | | 9.5 | | 39.17 |
| | | 8.4 | 11.92 | | | 8.9 | 39.92 |
| | 7.0 | | 21.67 | | 8.1 | | 49.71 |
| | | 6.8 | 22.46 | | | 7.9 | 50.38 |
| | 5.3 | | 29.42 | | 7.7 | | 64.42 |
| | | 5.2 | 30.08 | | | 7.2 | 65.13 |
| | | | | | 7.3 | | 71.88 |
| | | | | | | 7.0 | 72.58 |
| | | | | | 7.0 | | 79.38 |
| | | | | | | 6.6 | 80.04 |
| | | | | | 6.7 | | 88.17 |
| | | | | | | 6.2 | 88.92 |

| RUN | DISPLACEMENT (Degrees) L | DISPLACEMENT (Degrees) R | TIME (Seconds) | RUN | DISPLACEMENT (Degrees) L | DISPLACEMENT (Degrees) R | TIME (Seconds) |
|---|---|---|---|---|---|---|---|
| 5A | 13.8 | | 0.00 | 5B | 13.0 | | 0.00 |
| | | 9.2 | 0.88 | | | 10.0 | 0.96 |
| | 7.2 | | 1.71 | | 7.2 | | 1.79 |
| | | 5.6 | 2.50 | | | 6.1 | 2.67 |
| | 4.9 | | 3.29 | | 4.0 | | 3.54 |
| | | 3.6 | 4.08 | | | 4.1 | 4.33 |
| | 3.5 | | 4.88 | | 2.6 | | 5.17 |
| | | 2.0 | 5.67 | | | 2.8 | 6.04 |
| | 2.3 | | 6.50 | | 1.5 | | 7.00 |
| | | 1.3 | 7.38 | | | 1.9 | 7.71 |
| | 1.6 | | 8.17 | | 0.7 | | 8.71 |
| | | 0.9 | 8.96 | | | 1.2 | 9.38 |
| | 1.0 | | 9.83 | | 0.2 | | 10.42 |
| | | 0.3 | 10.63 | | | 1.0 | 11.13 |
| | 0.8 | | 11.38 | | 0.0 | | 12.08 |
| | | | | | | 0.7 | 12.86 |

APPENDIX B (Continued)

PENDULUM DAMPENING DATA

| RUN | DISPLACEMENT (Degrees) L | R | TIME (Seconds) |
|---|---|---|---|
| 6A | 13.4 | | 0.00 |
| | | 9.7 | 0.96 |
| | 7.8 | | 1.83 |
| | | 6.0 | 2.67 |
| | 5.1 | | 3.46 |
| | | 3.9 | 4.29 |
| | 3.3 | | 5.08 |
| | | 2.7 | 5.96 |
| | 2.1 | | 6.75 |
| | | 1.5 | 7.58 |
| | 1.1 | | 8.46 |
| | | 0.6 | 9.33 |
| | 0.9 | | 9.96 |
| | | 0.4 | 10.71 |

| RUN | DISPLACEMENT (Degrees) L | R | TIME (Seconds) |
|---|---|---|---|
| 6B | 12.5 | | 0.00 |
| | | 9.9 | 0.83 |
| | 7.5 | | 1.71 |
| | | 6.0 | 2.50 |
| | 5.0 | | 3.38 |
| | | 4.5 | 4.13 |
| | 3.2 | | 5.00 |
| | | 3.0 | 5.79 |
| | 2.0 | | 6.67 |
| | | 2.0 | 7.46 |
| | 1.4 | | 8.25 |
| | | 1.8 | 9.13 |
| | 1.0 | | 9.96 |
| | | 1.0 | 11.25 |
| | 0.5 | | 12.00 |
| | | 0.8 | 12.83 |
| | 0.2 | | 13.67 |
| | | 0.6 | 14.46 |

| RUN | DISPLACEMENT (Degrees) L | R | TIME (Seconds) |
|---|---|---|---|
| 7A | 13.1 | | 0.00 |
| | | 9.5 | 0.92 |
| | 7.4 | | 1.83 |
| | | 5.8 | 2.75 |
| | 4.3 | | 3.54 |
| | | 3.5 | 4.46 |
| | 2.7 | | 5.33 |
| | | 2.0 | 6.13 |
| | 1.5 | | 7.08 |
| | | 0.9 | 8.08 |
| | 0.8 | | 8.83 |
| | | 0.5 | 9.75 |
| | 0.3 | | 10.58 |

| RUN | DISPLACEMENT (Degrees) L | R | TIME (Seconds) |
|---|---|---|---|
| 7B | 12.5 | | 0.00 |
| | | 9.5 | 0.83 |
| | 7.1 | | 1.67 |
| | | 6.0 | 2.46 |
| | 4.1 | | 3.25 |
| | | 4.0 | 4.00 |
| | 3.0 | | 4.71 |
| | | 2.9 | 5.54 |
| | 2.0 | | 6.29 |
| | | 2.0 | 7.17 |
| | 1.0 | | 8.00 |
| | | 1.5 | 8.75 |
| | 0.5 | | 9.58 |
| | | 1.0 | 10.21 |
| | 0.4 | | 10.96 |
| | | 0.7 | 11.83 |

PENDULUM DAMPENING DATA

| RUN | DISPLACEMENT (Degrees) L | R | TIME (Seconds) |
|---|---|---|---|
| 8A | 14.3 | | 0.00 |
| | | 10.7 | 0.92 |
| | 8.5 | | 1.75 |
| | | 6.5 | 2.63 |
| | 5.5 | | 3.50 |
| | | 4.2 | 4.38 |
| | 3.5 | | 5.25 |
| | | 2.5 | 6.17 |
| | 2.2 | | 6.92 |
| | | 1.4 | 7.92 |
| | 1.3 | | 8.79 |
| | | 0.8 | 9.75 |
| | 0.7 | | 10.54 |
| | | 0.3 | 12.88 |
| | 0.1 | | 13.75 |
| 9A | 15.0 | | 0.00 |
| | | 10.5 | 0.96 |
| | 8.7 | | 1.79 |
| | | 6.7 | 2.63 |
| | 5.8 | | 3.46 |
| | | 4.3 | 4.25 |
| | 3.9 | | 5.08 |
| | | 2.9 | 5.88 |
| | 2.8 | | 6.67 |
| | | 1.9 | 7.50 |
| | 1.7 | | 8.38 |
| | | 1.0 | 9.21 |
| | 1.0 | | 10.08 |
| | | 0.5 | 10.88 |

| RUN | DISPLACEMENT (Degrees) L | R | TIME (Seconds) |
|---|---|---|---|
| 8B | 14.6 | | 0.00 |
| | | 10.1 | 0.88 |
| | 7.9 | | 1.71 |
| | | 6.0 | 2.54 |
| | 5.3 | | 3.29 |
| | | 4.9 | 4.08 |
| | 3.4 | | 5.00 |
| | | 2.9 | 5.71 |
| | 2.7 | | 6.54 |
| | | 1.9 | 7.38 |
| | 1.9 | | 8.17 |
| | | 1.0 | 8.96 |
| | 1.2 | | 9.67 |
| | | 0.8 | 10.38 |
| 9B | 14.0 | | 0.00 |
| | | 10.3 | 0.83 |
| | 8.1 | | 1.71 |
| | | 6.1 | 2.46 |
| | 5.2 | | 3.21 |
| | | 4.2 | 4.04 |
| | 3.8 | | 4.79 |
| | | 3.1 | 5.63 |
| | 2.5 | | 6.50 |
| | | 2.0 | 7.29 |
| | 1.9 | | 8.17 |
| | | 1.5 | 8.96 |
| | 1.3 | | 9.79 |
| | | 1.0 | 10.58 |

APPENDIX B (Continued

PENDULUM DAMPENING DATA

| RUN | DISPLACEMENT (Degrees) L | R | TIME (Seconds) | RUN | DISPLACEMENT (Degrees) L | R | TIME (Seconds) |
|---|---|---|---|---|---|---|---|
| 10A | 15.0 | | 0.00 | 10B | 14.6 | | 0.00 |
| | | 10.1 | 0.92 | | | 10.1 | 0.88 |
| | 8.2 | | 1.67 | | 7.9 | | 1.71 |
| | | 6.2 | 2.50 | | | 6.0 | 2.54 |
| | 5.5 | | 3.38 | | 5.3 | | 3.29 |
| | | 4.0 | 4.17 | | | 4.2 | 4.08 |
| | 3.8 | | 4.92 | | 3.4 | | 5.00 |
| | | 2.8 | 5.75 | | | 2.9 | 5.71 |
| | 2.5 | | 6.58 | | 2.7 | | 6.54 |
| | | 1.9 | 7.33 | | | 1.9 | 7.38 |
| | 2.0 | | 8.17 | | 1.9 | | 8.17 |
| | | 1.0 | 9.00 | | | 1.0 | 8.96 |
| | 1.3 | | 9.83 | | 1.2 | | 9.67 |
| | | 0.7 | 10.58 | | | 0.8 | 10.38 |

APPENDIX C

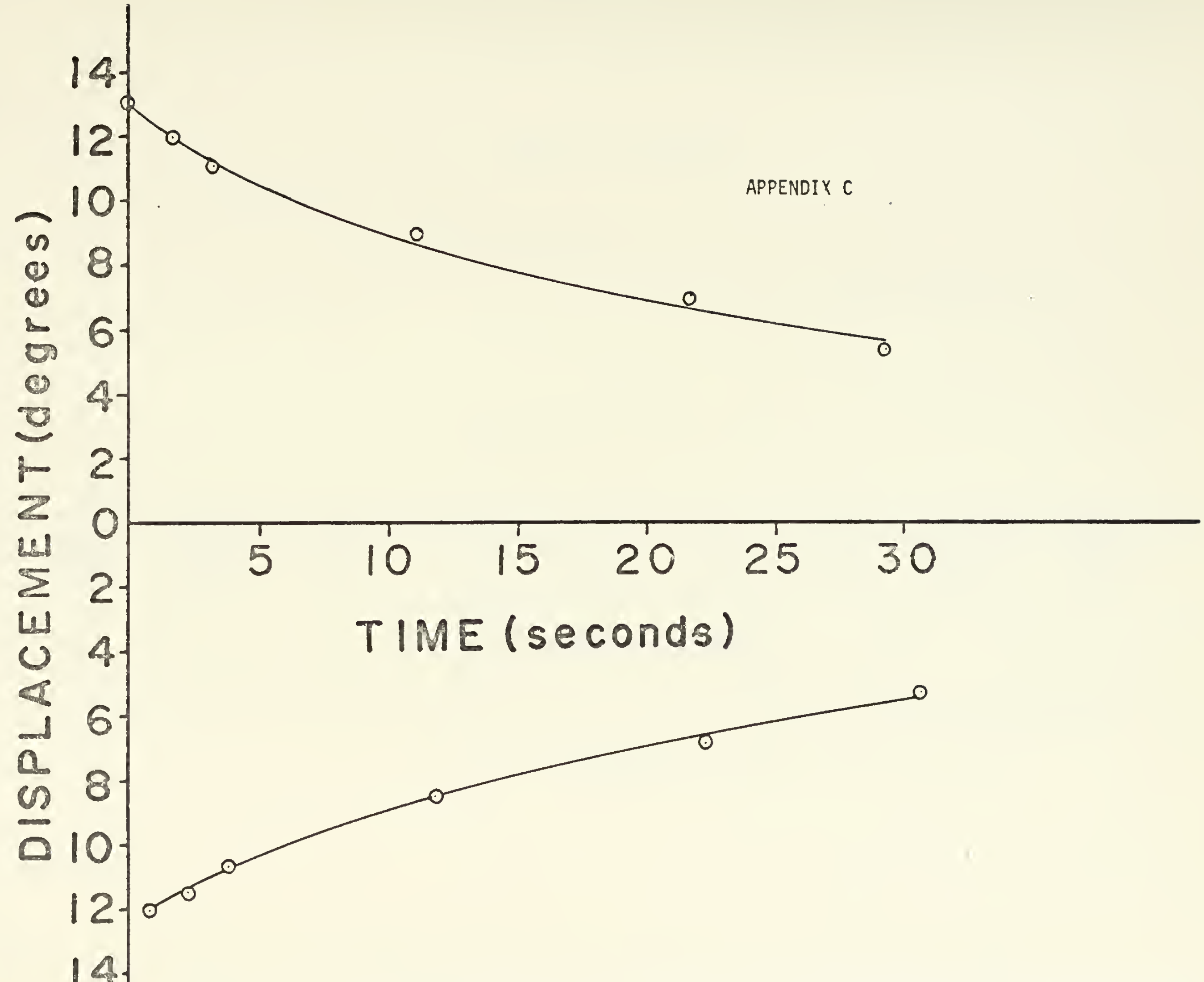


FIGURE 28. FREE VIBRATION CURVE FOR AIR DAMPENING WITH 18 POUND PENDULUM WEIGHT ABOUT THE A AXIS

APPENDIX C (CONTINUED)

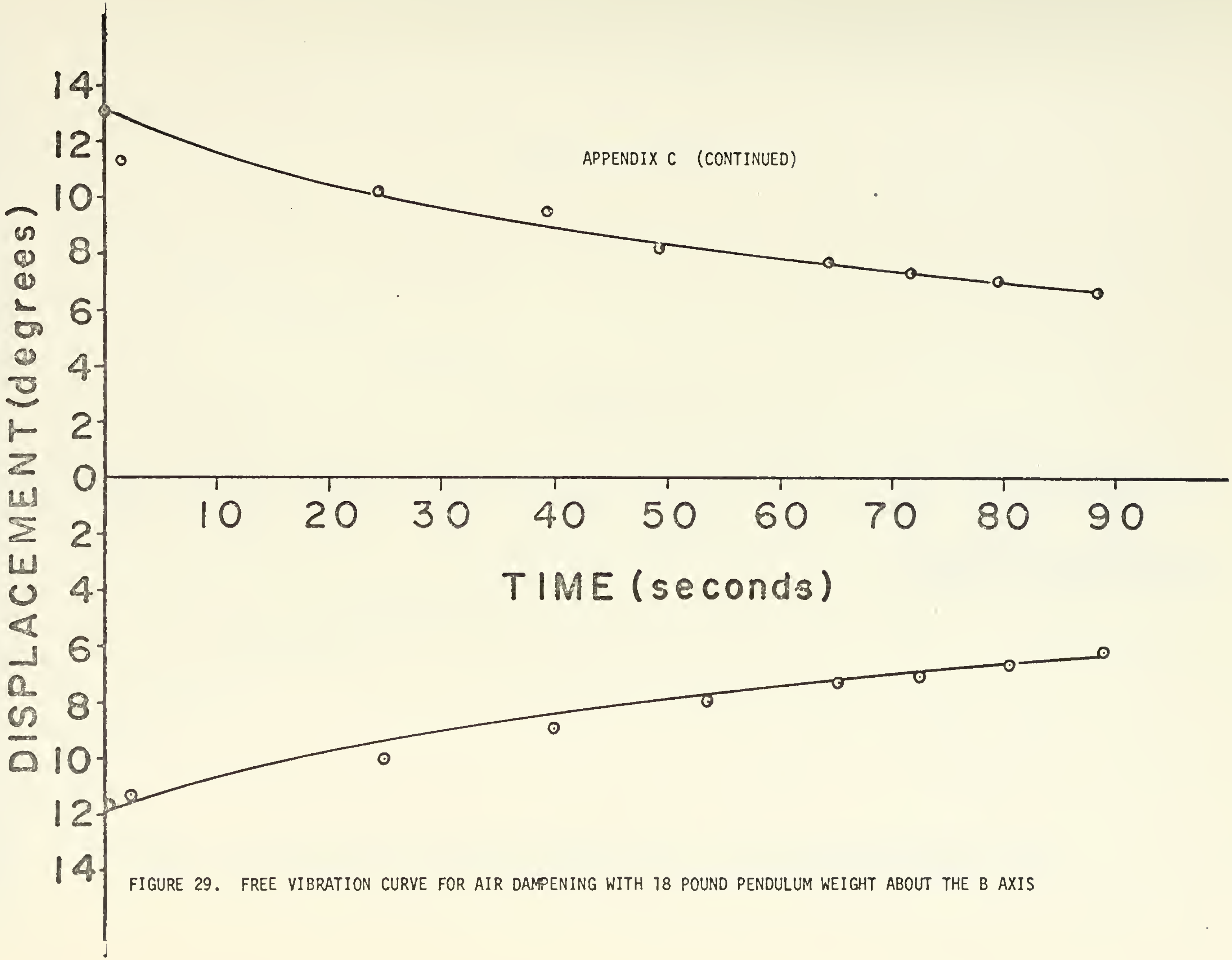


FIGURE 29. FREE VIBRATION CURVE FOR AIR DAMPENING WITH 18 POUND PENDULUM WEIGHT ABOUT THE B AXIS

APPENDIX C (CONTINUED)

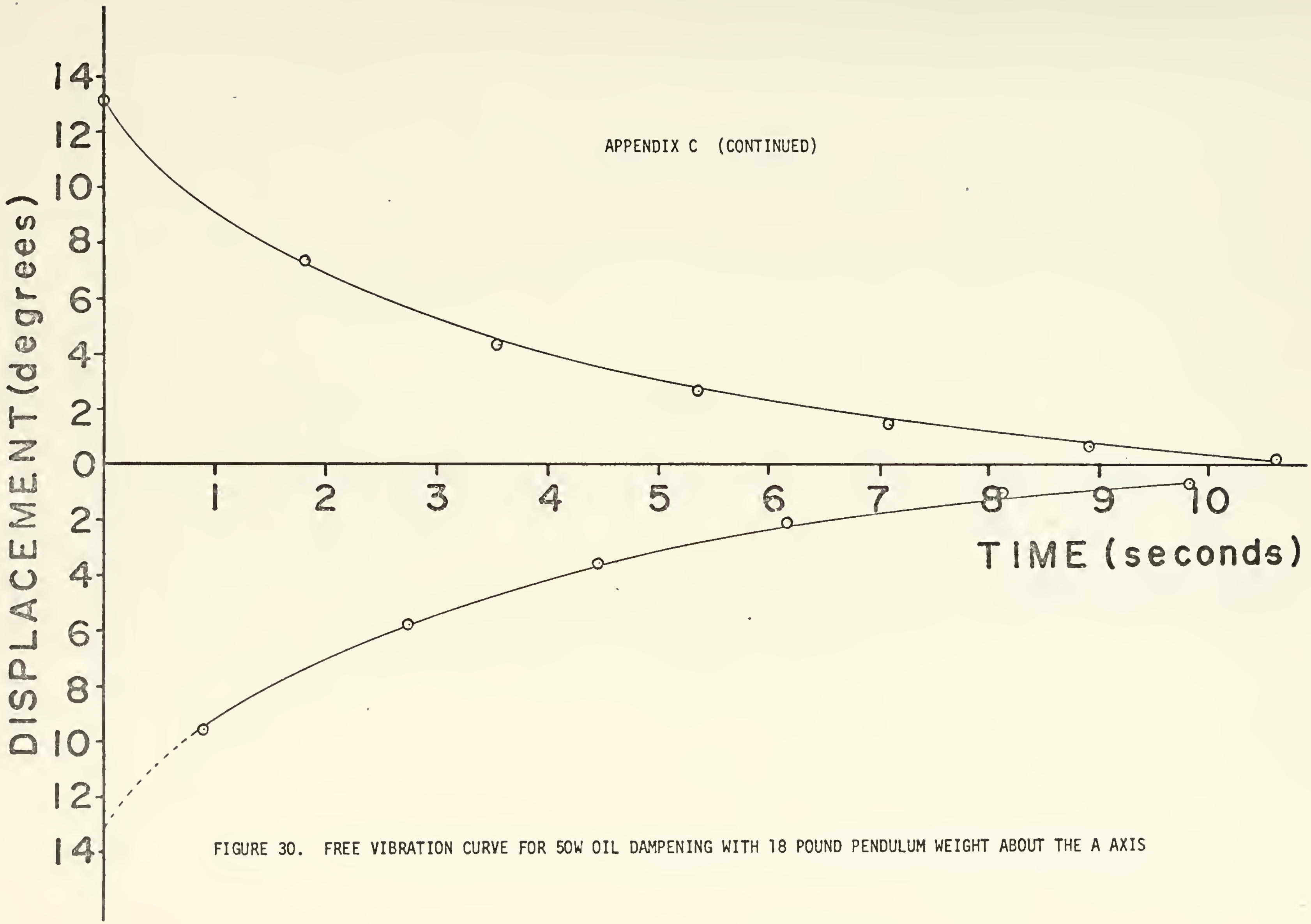


FIGURE 30. FREE VIBRATION CURVE FOR 50W OIL DAMPENING WITH 18 POUND PENDULUM WEIGHT ABOUT THE A AXIS

APPENDIX C (CONTINUED)

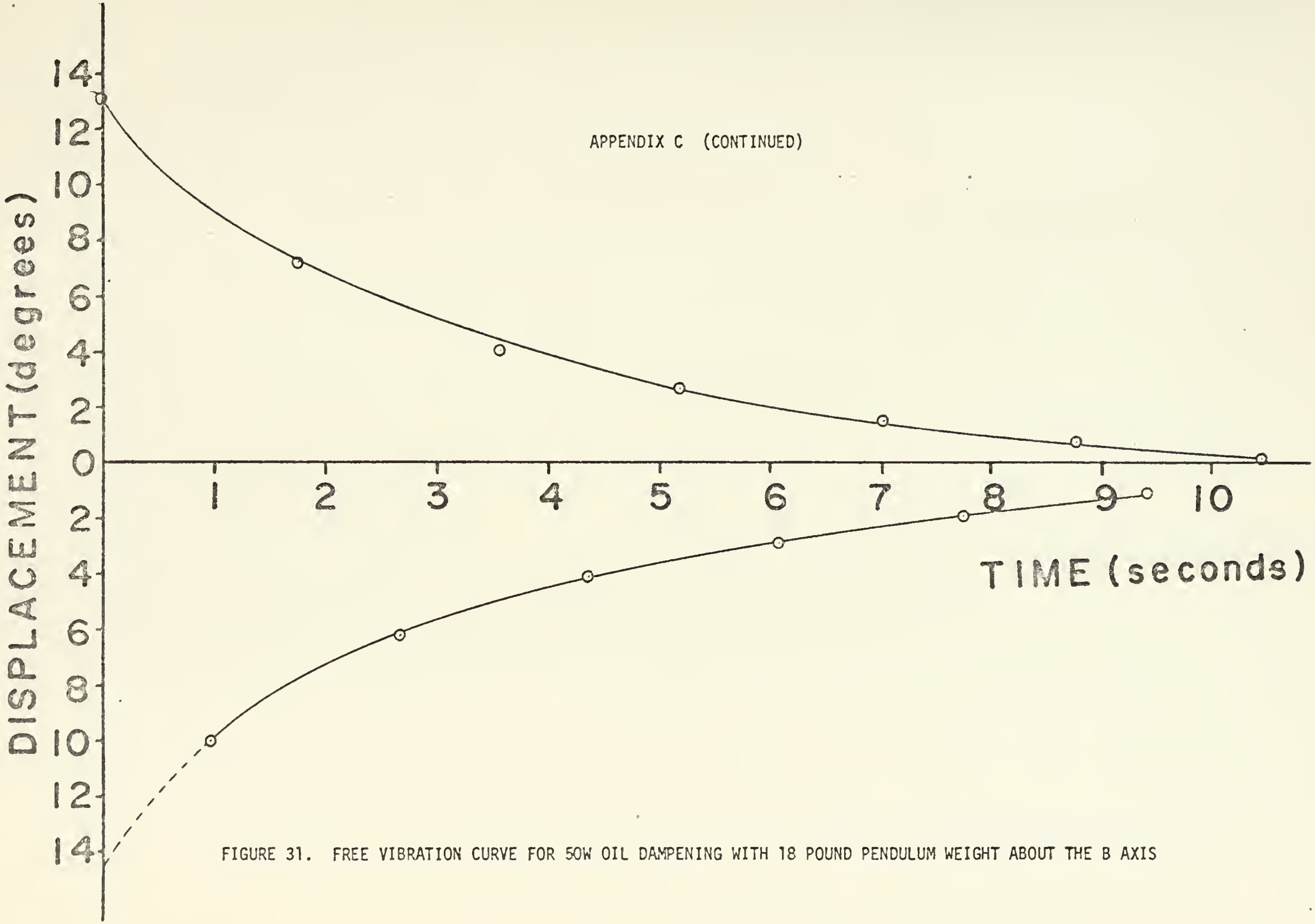


FIGURE 31. FREE VIBRATION CURVE FOR 50W OIL DAMPENING WITH 18 POUND PENDULUM WEIGHT ABOUT THE B AXIS

APPENDIX C (CONTINUED)

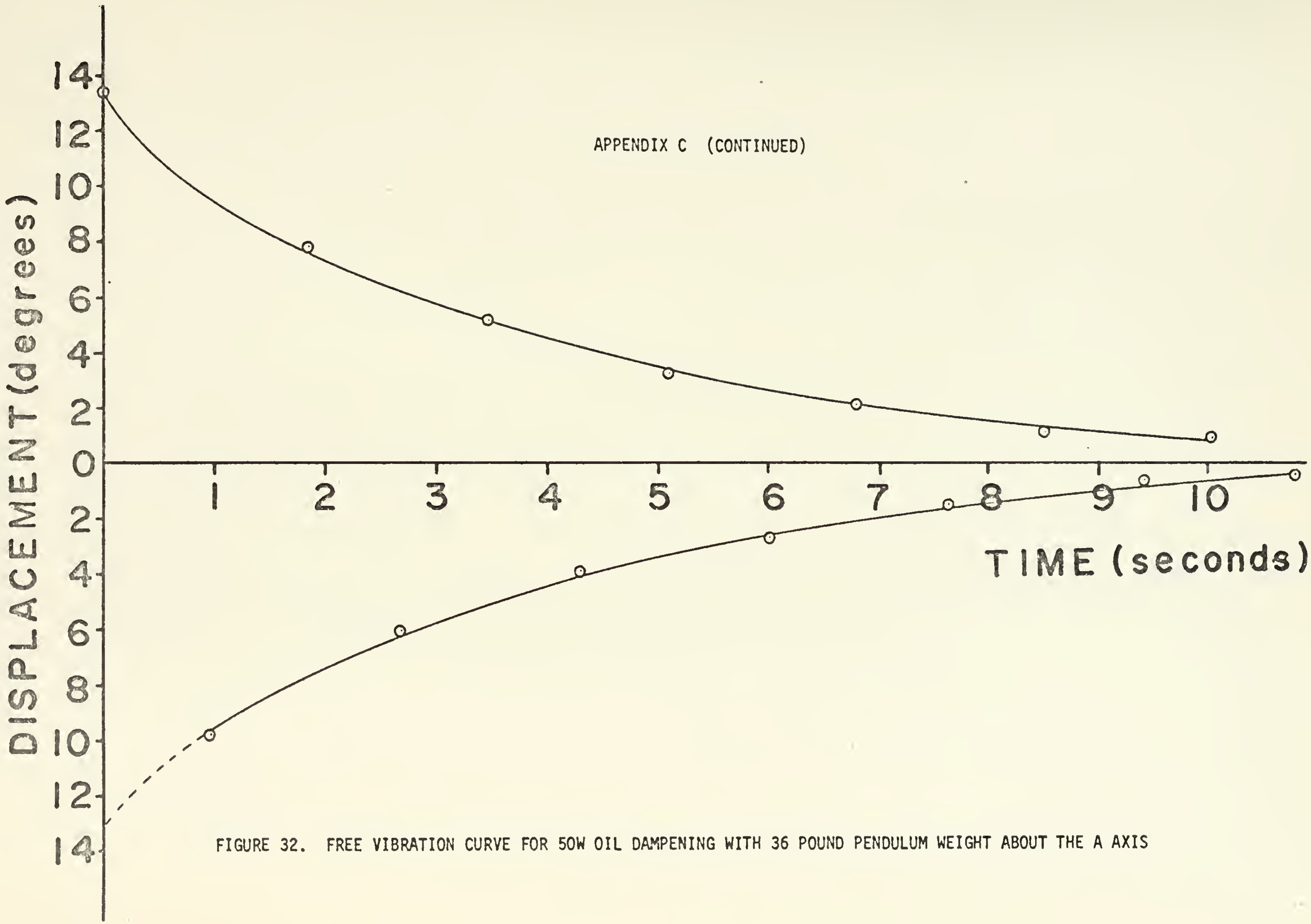


FIGURE 32. FREE VIBRATION CURVE FOR 50W OIL DAMPENING WITH 36 POUND PENDULUM WEIGHT ABOUT THE A AXIS

APPENDIX C (CONTINUED)

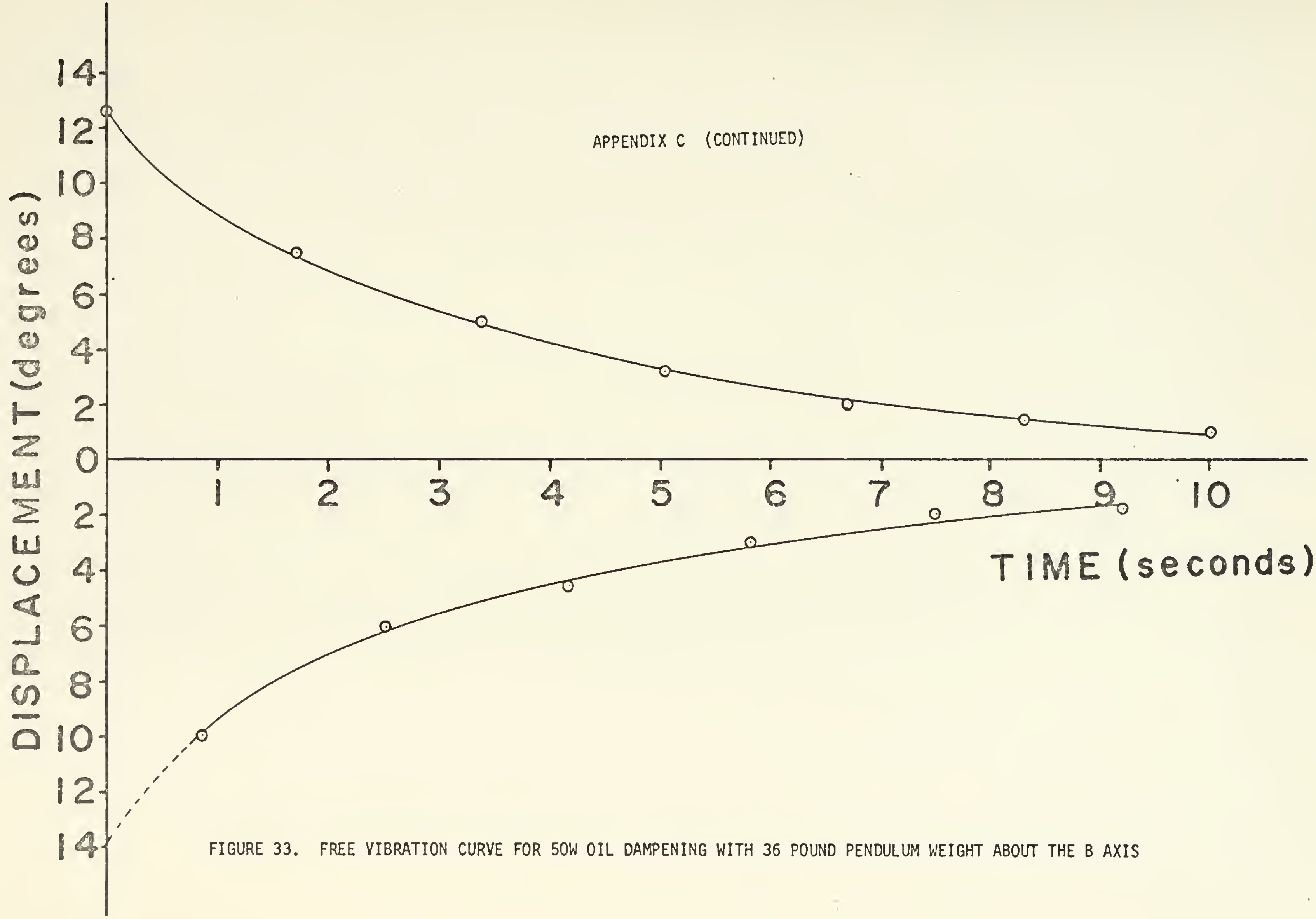


FIGURE 33. FREE VIBRATION CURVE FOR 50W OIL DAMPENING WITH 36 POUND PENDULUM WEIGHT ABOUT THE B AXIS

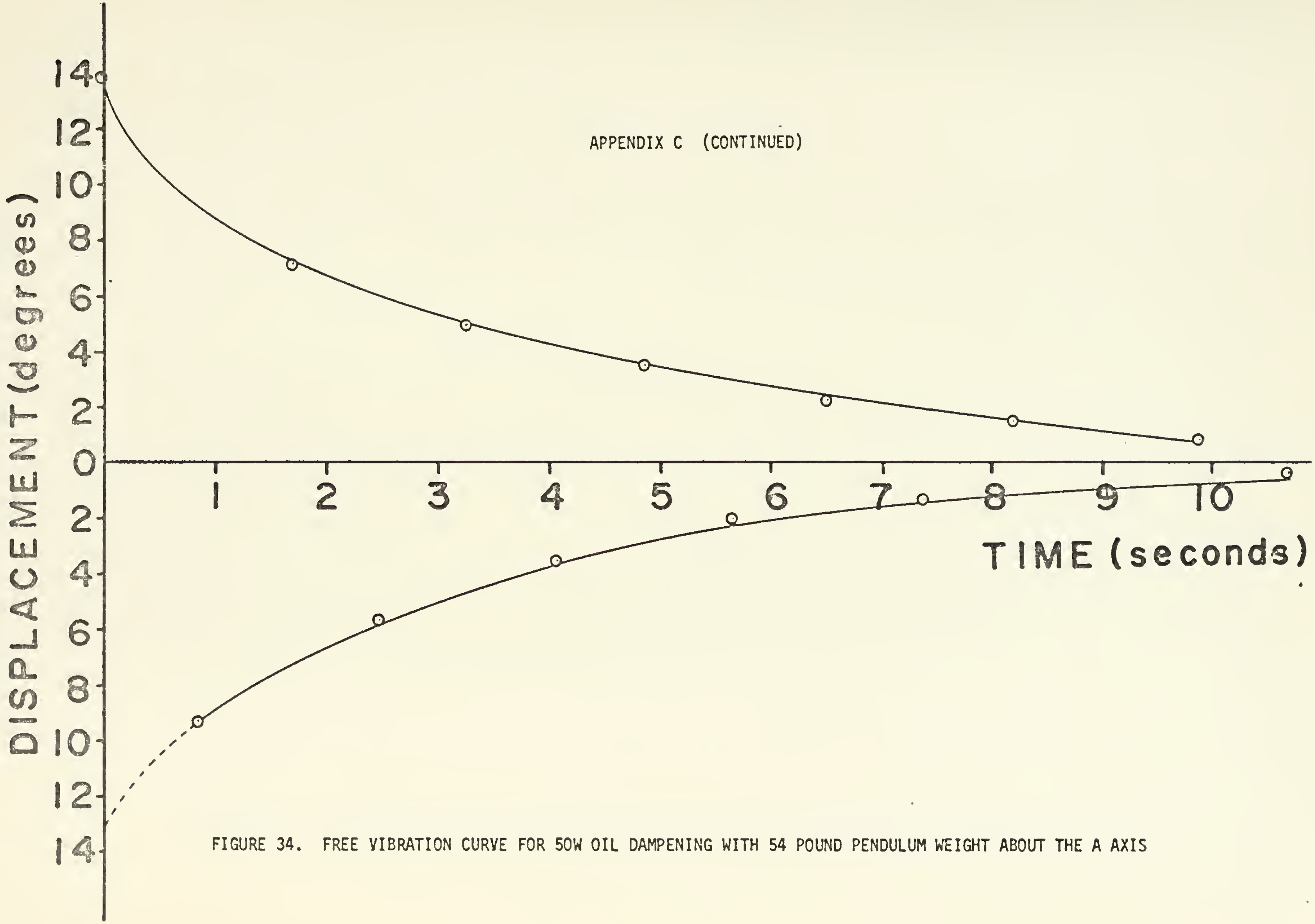


FIGURE 34. FREE VIBRATION CURVE FOR 50W OIL DAMPENING WITH 54 POUND PENDULUM WEIGHT ABOUT THE A AXIS

APPENDIX C (CONTINUED)

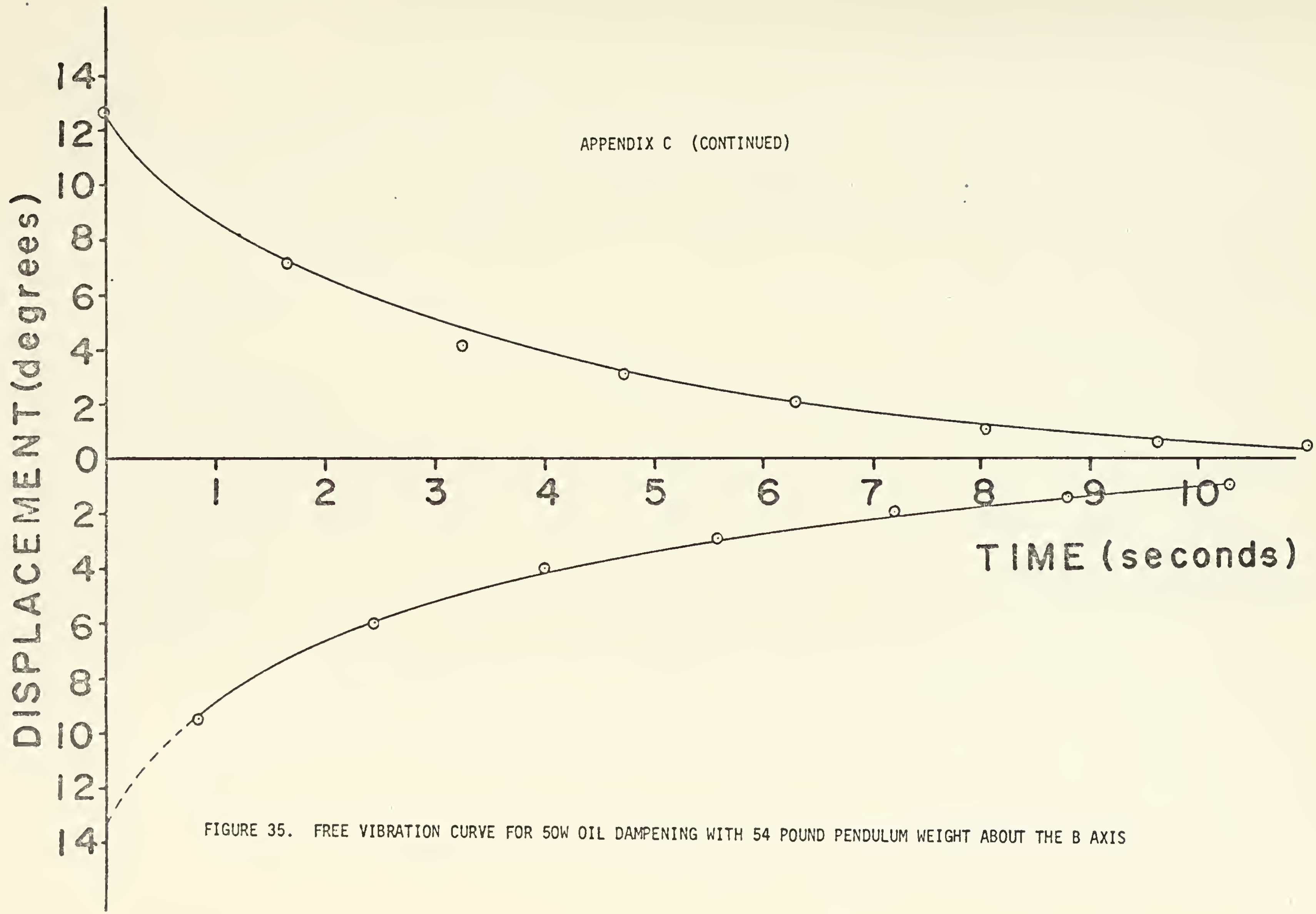


FIGURE 35. FREE VIBRATION CURVE FOR 50W OIL DAMPENING WITH 54 POUND PENDULUM WEIGHT ABOUT THE B AXIS

APPENDIX C (CONTINUED)

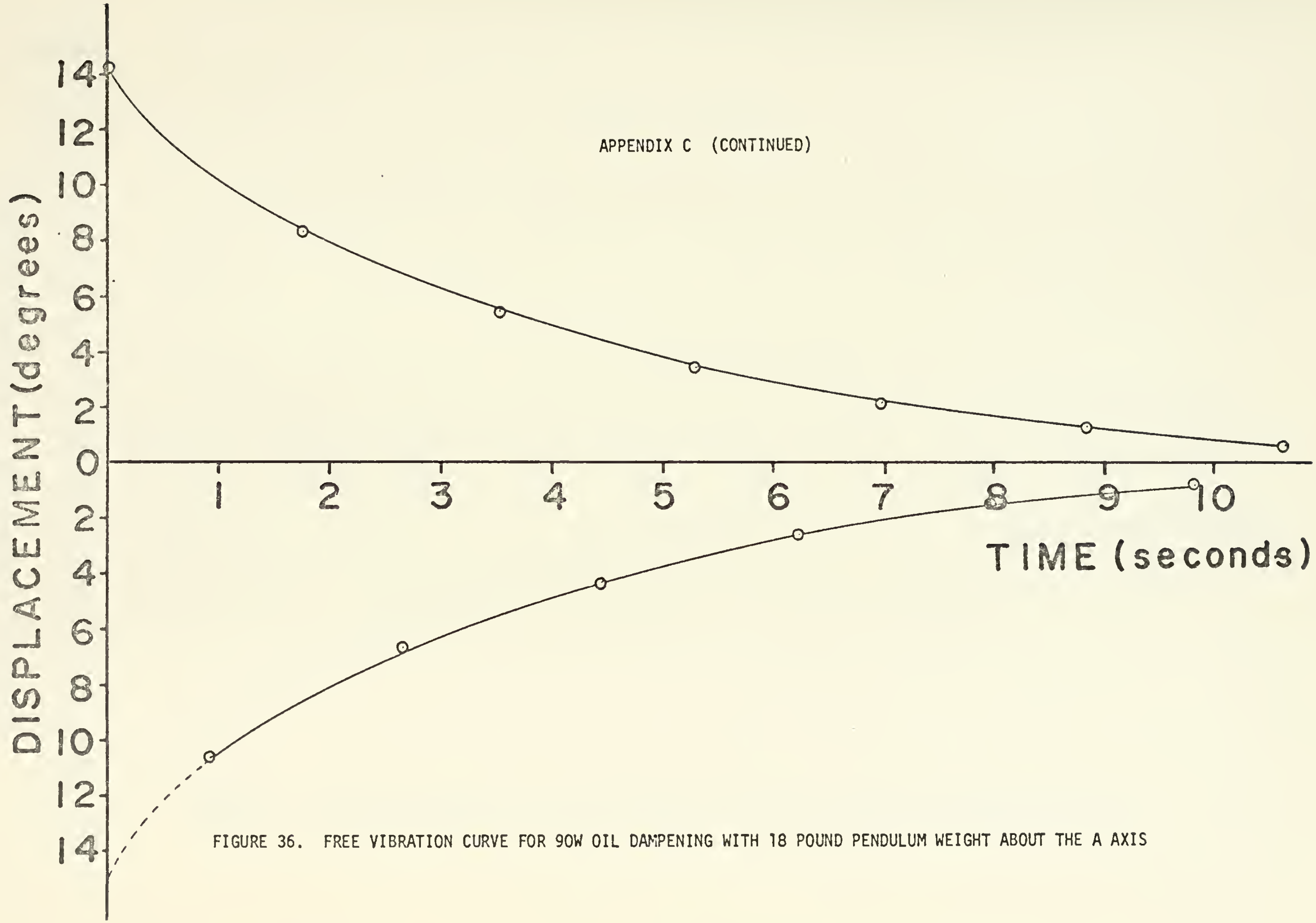


FIGURE 36. FREE VIBRATION CURVE FOR 90W OIL DAMPENING WITH 18 POUND PENDULUM WEIGHT ABOUT THE A AXIS

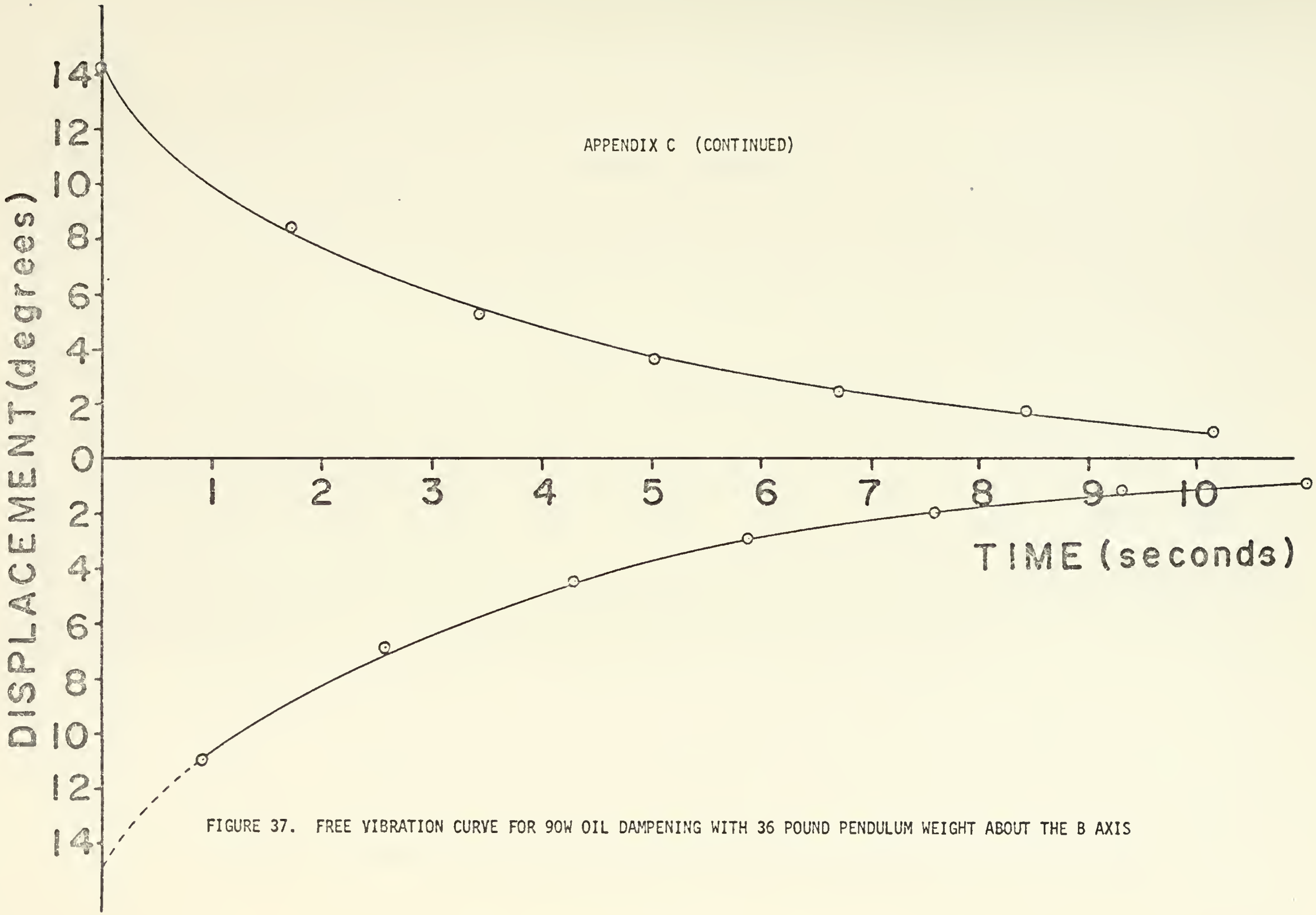


FIGURE 37. FREE VIBRATION CURVE FOR 90W OIL DAMPENING WITH 36 POUND PENDULUM WEIGHT ABOUT THE B AXIS

APPENDIX C (CONTINUED)

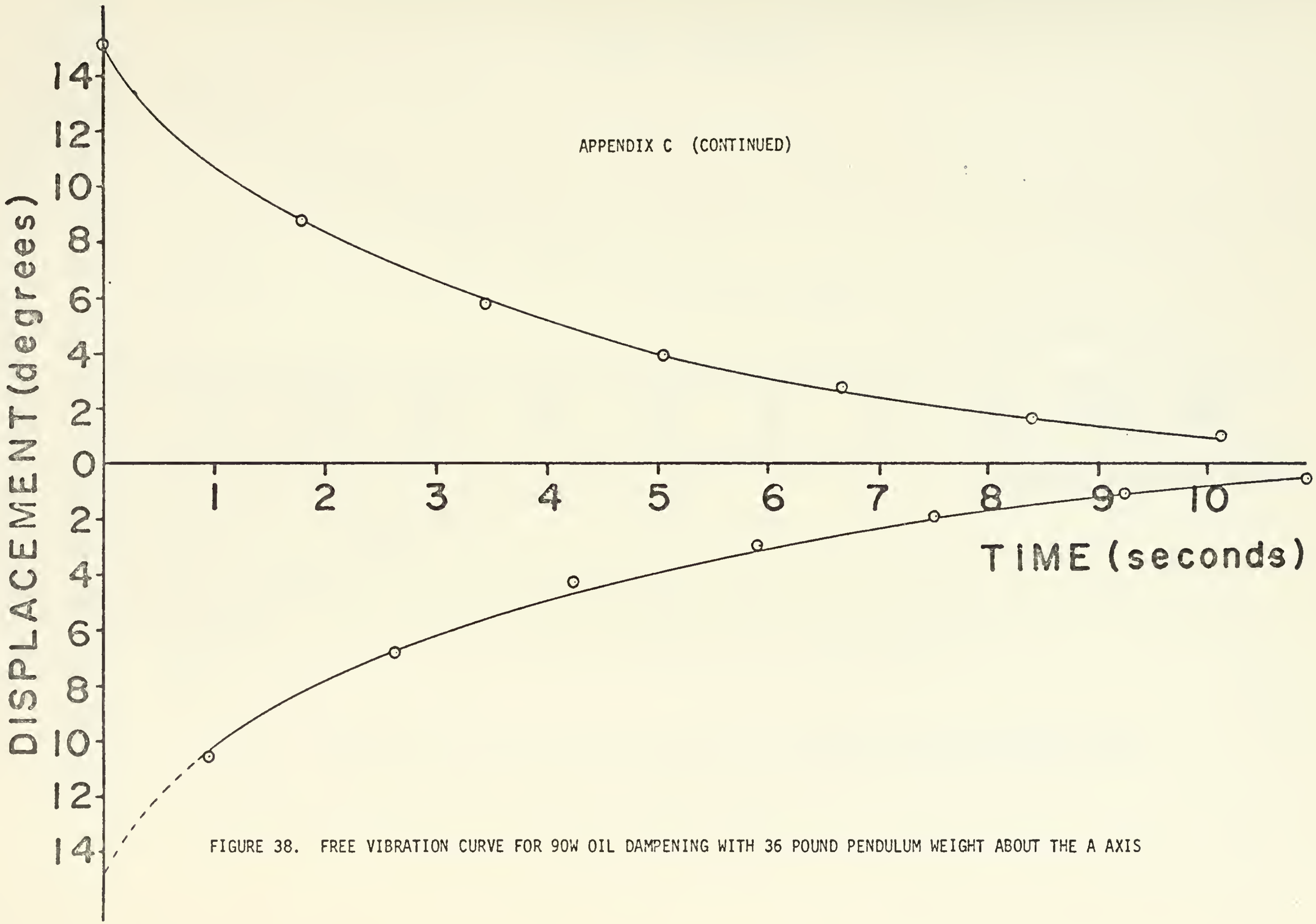


FIGURE 38. FREE VIBRATION CURVE FOR 90W OIL DAMPENING WITH 36 POUND PENDULUM WEIGHT ABOUT THE A AXIS

APPENDIX C (CONTINUED)

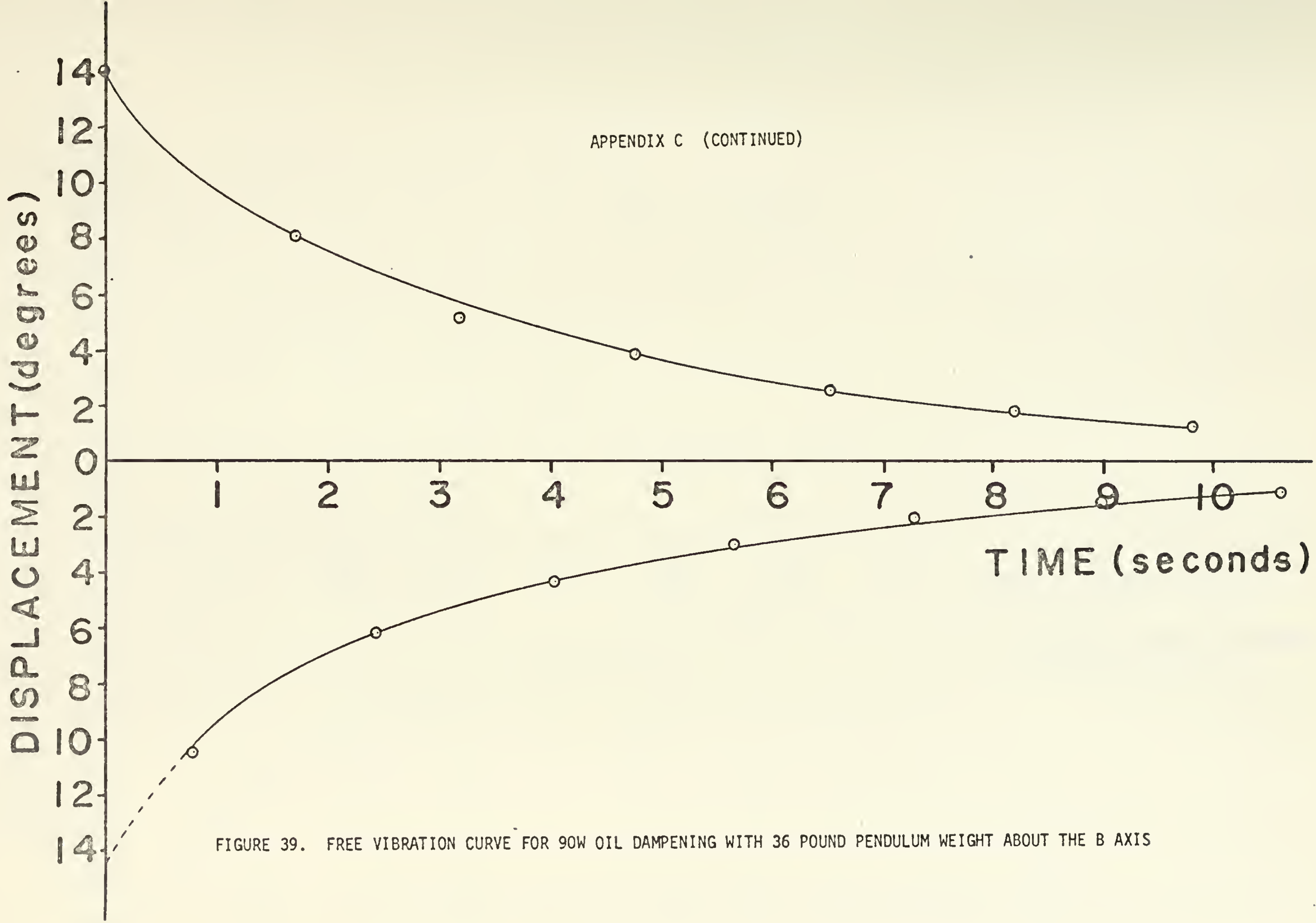


FIGURE 39. FREE VIBRATION CURVE FOR 90W OIL DAMPENING WITH 36 POUND PENDULUM WEIGHT ABOUT THE B AXIS

APPENDIX C (CONTINUED)

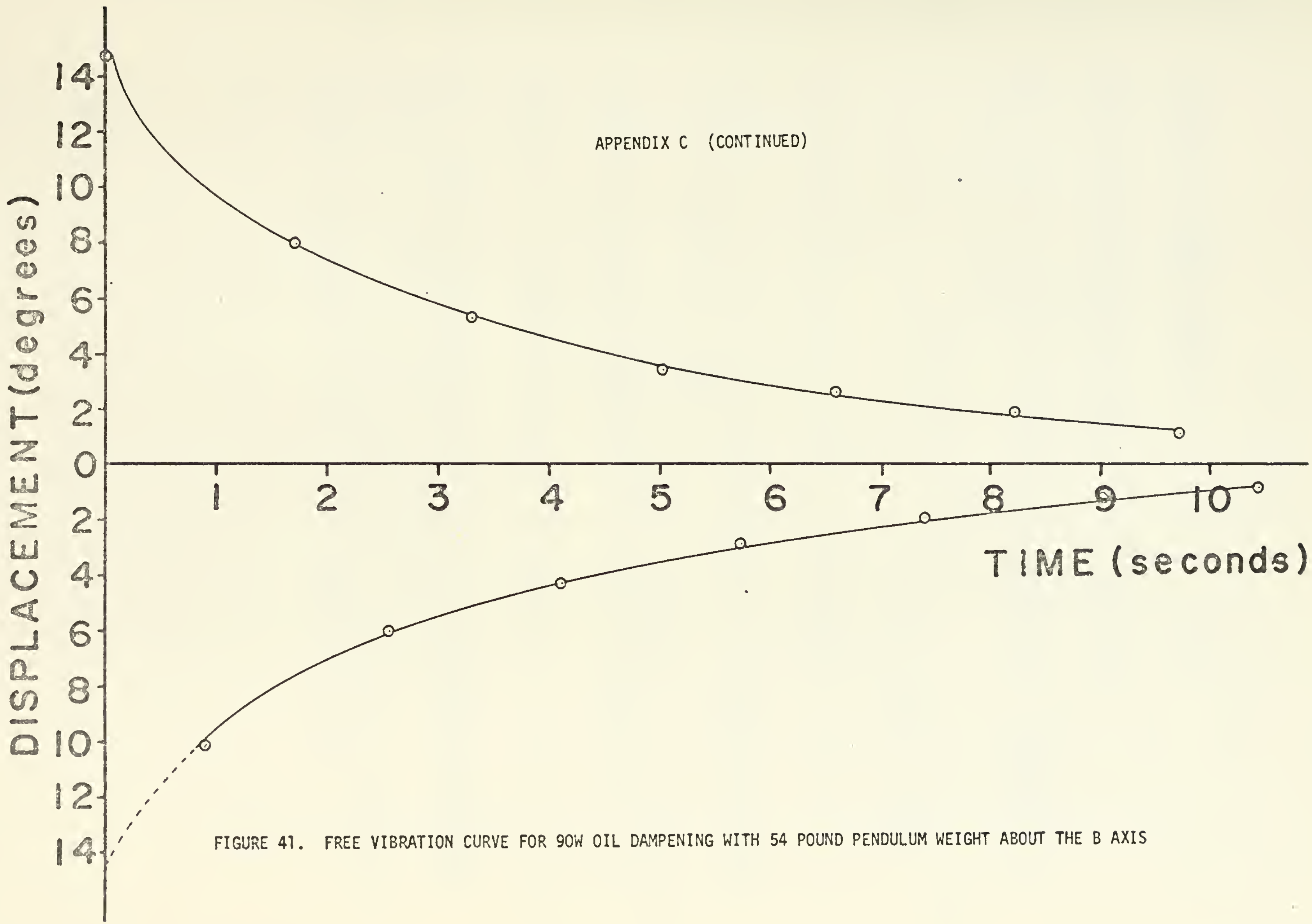


FIGURE 41. FREE VIBRATION CURVE FOR 90W OIL DAMPENING WITH 54 POUND PENDULUM WEIGHT ABOUT THE B AXIS

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13. ABSTRACT

The use of a gimbal platform with two degrees of freedom under dampened pendulum motion allows a standard laboratory balance to be used to weigh scientific samples at sea. The maximum sample weight tested was approximately 120 grams, while the average accuracy obtained in samples ranging from 1 to 120 grams was 0.10% (± .05%). The sea conditions under which at-sea weighings can be conducted vary with the size of the research vessel. The gimbal platform does not provide the stabilization necessary under adverse sea conditions.

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Security Classification

A-31408

| 14 KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Weighing | | | | | | |
| Balance | | | | | | |
| Pendulum Motion | | | | | | |
| Gimbal Platform | | | | | | |

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c.1 Weighing at sea
with a gimbal platform.